Answer to N. Pirk

The comments of the reviewer are in black, our reply is coloured blue.

The manuscript presents land-atmosphere methane fluxes from a permafrost-underlain wetland in NE Siberia, with a special focus on short-term fluctuations caused by non-turbulent conditions. The analysis uses wavelet transforms to calculate fluxes with higher time resolution than conventional eddy covariance calculations, also in non-turbulent conditions when the ground surface is (or has been) decoupled from the sensor level. Based on the wavelet flux time series, high-flux events are identified and classified according to their temporal structure. Some specific events are described in detail to distinguish the active mesoscale processes. The work should be interesting for many in the eddy covariance community and is relevant for the scope of ACP. The language and figures are of good quality. I therefore recommend the publication of this manuscript after minor revision considering my comments below.

We thank Norbert Pirk for his constructive comments. According to his remarks we revised our manuscript as described in the following reply.

1. Generally speaking, it is important to have studies that present alternatives to the conventional eddy covariance flux calculations. After reading this manuscript, however, I am left with the impression that wavelet flux estimations give arbitrary flux results. You used two different wavelets, the Mexican Hat and the Morlet, and get flux differences by about 30% on average (cf. Table 1). Other wavelets might have given even larger differences. I think this makes it difficult for the wider EC community to apply the wavelet analysis approach. While I understand that you cannot resolve this arbitrariness in your manuscript, I think you should be clearer about the potential and the shortcomings of wavelet flux calculations.

The reason for these differences in the calculated flux of the event shown in the case study in section 3.4 including Table 1 is directly connected to the mathematical behaviour of the mother wavelet. The Morlet wavelet allows a very good resolution in the frequency domain while its localization in the time domain is not that good (e.g. Collineau and Brunet, 1993). In our manuscript we used an averaging time of 30 minutes, which is widely used for eddy covariance processing. Usually this is not problematic in times of well-developed turbulence, because then the longest period contributing significantly to the flux should be 30 minutes (e.g. Charuchittipan et al., 2014; Foken et al., 2006). As already shown by Schaller et al., 2017, in times of well-developed turbulence, the results of both Mexican hat and Morlet wavelet are comparable and their deviation is within the typical error range of eddy covariance.

In the current manuscript we analyze fluxes also during times with only little or nearly no turbulence. Table 1 as well as Figure 4 (for tower 2) show the differences of the averaged flux magnitude over 30 minutes as mentioned by Norbert Pirk for the discussed event in section 3.4. The two upper panels show the wavelet cross scalograms for both wavelets. Exemplarily discussed for tower 2 and the Morlet wavelet, the area of high energy is sharp in frequency domain but shows a smearing effect in time domain from Aug 2, 23:00 to Aug 3, 0:45. The Mexican hat wavelet, on the other hand, resolves the event exactly in time domain (Aug 2, 23:59 – Aug 3, 0:07) while the resolution in frequency domain is slightly – but negligible – worse, compared to Morlet. These differences in resolution also explain the differences in the averaged flux over 30 minutes from 0:00 to 0:30. Both the Morlet wavelet flux (147 nmol m^{-2} s^{-1}) and the eddy covariance flux (179 nmol m^{-2} s^{-1}) underestimate the flux compared to Mexican hat (213 nmol m^{-2} s^{-1}).

To obtain similar results at least for the two wavelets, it is necessary to extend the averaging period, i.e., the averaging period should be longer than the smallest contributing frequency. For the eddy covariance method it won't be possible in this case, because the steady-state assumption is not fulfilled.

To sum up: as long as we keep the fixed averaging period of 30 minutes, the Morlet wavelet is not able to resolve the event completely while the Mexican hat wavelet delivers exact and authoritative results. We agree to Norbert Pirk that the shortcomings of Morlet compared to Mexican hat wavelet were not described sufficiently in our manuscript. The findings and scalograms of the Morlet wavelet can be used as some kind of a complex measure for stationarity / steady-state-conditions, which extends the stationarity test after Foken and Wichura (1996) by an ogive test – but this might lead to misunderstandings; we also did not mention that clear enough in our manuscript.

As the aim of our paper is on the characterisation of single short-term events and not on the flux over a longer time, **we decided to remove the results of the Morlet wavelet**, because 1) they might confuse the reader and 2) they don't add significant information to the findings and results. Instead we will add a paragraph in section 2 about the choice of a proper mother wavelet (here: Mexican hat).

2. You imply on several occasions that the high-flux events you identified are related to methane emissions from the ecosystem. For example, when you relate event occurrences to soil temperatures in the abstract (page 1, lines 9ff, "We demonstrate..."). Also many other parts of your manuscript are written as if this study is about bio-physical processes, and not just about a different flux calculation method. At the same time, I think you are aware that your events are probably not ecosystem emissions, but merely a venting of previously accumulated methane. The fluxes you present, e.g. in Figure 1, indicate fast shifts between methane emission and uptake, which are unlikely to have anything to do with the ecosystem dynamics. There is a tendency throughout your manuscript to smear out the distinction between the ecosystem methane exchange and the flux you calculate at sensor level.

In fact, in our manuscript we also give a short information on the event seasonality (section 3.2), i.e. the number of occurrence of events during the time. It is known that increasing soil temperature changes the microbial decomposition rates of organic matter (e.g., Anderson, 1992; Valentine et al., 1994) and we could show that there is indeed a positive connection between the number of events and the soil temperature. Of course, the occurrence of meso-scale processes does not depend on soil temperature or other processes in the soil or the ecosystem, but it is an indirect measure for the activity of methanogenesis in soil that leads to a release of CH_4. So, e.g., during the observed maximum mean of the soil temperature in the first half of August, also the amount of methane released per time reached its maximum. E.g., during stable stratification in early August the biggest amount of CH4 gets accumulated per time close to the ground and later suddenly be released, in comparison to other months. **We will revise our manuscript so that this connection is clearly understandable.**

We agree that it is important to distinguish between methane emissions from the footprint of the EC system and emissions from around that were transported to the tower. Especially in the case of horizontal advection being the driver, the methane being vented to the EC system might originate partly from outside of the footprint. For regular flux calculations, especially for long-term balances and the discussion of biosphere-atmosphere interactions, this might definitely be a big issue. On the other hand, our investigations of advection in this study aim to show the impact of this meso-scale trigger on the flux in a one minute resolution using wavelet analysis. **We will add some sentences to emphasize that the behaviour of the high resolution flux during the discussed advection event is not due to ecosystem dynamics but due to the venting of the accumulated and advected methane.**

3. On a related note, you mention that conventional EC processing would give biased budgets due to events of non-turbulent mixing, even if filtering and gap-filling is applied. However, you don't perform the comparison to a commonly-used filtering and gap-filling routine to make such a statement. If you want to say anything about such a possible bias, your analysis needs to show this.

Our manuscript explicitly investigates single events, that would usually be removed by gap-filling algorithms, but does not target long-term results. Such an extension of our manuscript by long-term studies including error analysis would be beyond the scope of this article. Nonetheless, we definitely agree that a comparison of wavelet fluxes and EC fluxes as well as EC gap filling approaches over a longer period should be performed to quantify its effect-term balances. This would be an interesting additional paper for future, which is already in preparation in our working group. **We will add this information to the revised manuscript; we will also revise the mentioned note, so that it is clear to the reader that we did not analyse this and that there will be a future paper analyzing the impact on long-term results in detail.**

4. You attribute parts of the high-flux events to methane that entered your footprint by horizontal advection. But since you have no direct measurements of horizontal methane advection, this attribution remains speculative in this study and should be phrased accordingly.

We agree, that it is much more difficult to detect advection without direct gradient profile measurements. Please see in general also our answer to your specific comment 7 concerning this point. Specifically to your question on advection events, Figure 6 in the manuscript supports this finding, because it directly shows the approaching fog bank. The occurrence and arrival of this fog bank at the towers exactly in time with the observed event in the data clearly indicates advection. Also in literature such kind of fog events are classified directly as advection fog (e.g., Stull, 1988).

5. I think your dataset of methane EC measurements from NE Siberia is impressive and extremely valuable, but in this manuscript you don't use this potential very much: you say and conclude little about this ecosystem or the methane dynamics of it. I understand that you want to focus on wavelet analysis and short-term events, but you could probably have done this for much easier field studies (something like CO2 exchange above a central European farmland). You don't even mention your field site location in the abstract. I think there is room for improvement to integrate and connect your findings to methane flux studies from permafrost wetlands.

Yes, we generally agree, that there are many easier ways to obtain datasets that contain influences of meso-scale processes like advection or weather fronts passing the site, e.g., in Germany instead of going to a very remote and difficultly accessible site in the Russian Far East. However, the original intention of our study was the identification of ebullition events using high frequency data from EC towers. Ebullition is a quite important CH_4 emission pathway in permafrost wetlands and therefore currently a big subject of research in the community. As you know from our manuscript, we could not encounter any signs of ebullition in the data. Instead we found wavelet analysis being capable to resolve periods of the dataset where the steady-state assumption was not fulfilled. While this manuscript investigates specific events in detail, a follow-up paper will compare the wavelet results with common gap-filling routines, yielding information on its influence to the long-term balances.

Luckily, our manuscript is also not the only study that originates from this indeed extremly valuable dataset. So, based on that dataset, there are already published studies on the impact of a persistently lowered water table on CO_2 and CH_4 emissions (Kittler et al., 2016, 2017) as well as on the energy fluxes (Göckede et al., 2017). Additionally, the dataset was also already useful to compare results of a year-round CH_4 simulation model on CH_4 emissions with real data (Castro-Morales et al., 2018).

We will emphasize the information on our follow-up paper and also add the field site location to the abstract.

Specific comments:

6. Page 1, line 5 You mention that ebullition events last for only a few minutes, but I think the timescale of ebullition depends on the spatial scale. On a small spatial scale, maybe comprising a single bubble only, an ebullition event would probably only take seconds to be mixed into the ambient atmosphere.

Yes, the timescale of ebullition depends on the spatial scale. **We will change this sentence.**

7. Page 1, lines 12ff. "By investigating..." This sentence is unclear. You say you identified mesoscale processes as the dominating processes. But for what? You mean as the trigger for high-flux events? But then this is quite a stretch given your rather descriptive analysis of the mesoscale conditions.

Yes, we generally agree that it is difficult to link the found high flux events to the identified mesoscale processes. Your question is similar to general comment 3 by Anonymous Referee #2, which we both answer as follows:

Based on our meteorological measurements, we conclude that the identified mesoscale processes triggered the observed high-flux events. We agree that it is somehow “a stretch” or “speculative”, to identify these mesoscale phenomena without measurements of spatial (vertical / horizontal) profiles. Usually, periods consisting of phenomena like the found mesoscale processes, are replaced by gap filling algorithms during the standard eddy covariance processing. Long-term measurements of the atmospheric boundary layer, including devices like SODAR-RASS or LIDAR as well as arrays of other vertical / horizontal gradient measurements, could fill this gap. Long-term measurements are necessary here, because these phenomena are not detected very often and any statistical analysis is nearly impossible then.

Nonetheless we think, that it will be worth to publish observations of such relatively rare phenomena if it is possible to observe them. The detection, identification and differentiation of such mesoscale phenomena requires considerable experience. Such experience is fortunately available in our working group, considering, e.g., the publications by Foken et al. (2012) or Serafimovich et al. (2018), where surface flux measurements and boundary-layer measurements were available. Of course, we carefully discussed the identified processes within our working group, to be as sure as possible in our statements regarding the available data. For the identification of these mesoscale processes we used the data from both towers (distance: 600 m). Here it is important to know that the identified phenomena are always visible at both tower 1 and 2, which supports our findings. **This was not mentioned clearly in the manuscript, so we will emphasize this information.**

To sum up, the classification of the different mesoscale processes is still not completely satisfying, but also not fully speculative. We will carefully revise the manuscript, so that it is clear for the reader why the identification is not just speculative.

8. Page 1, lines 15f. "It is a reliable..." Please elaborate and clarify this statement. How exactly can I evaluate the flux quality using wavelets? And did you show that this works reliably?

Your question is quite similar to general comment 2) by Anonymous Referee #2. Thus, we answer both as follows: using a mother wavelet with an exact resolution in time domain like the Mexican hat wavelet yields the exact flux by integrating over a short time interval, e.g., 1 min. In this case also all parts in the frequency domain that contribute to the flux are included and considered (Percival and Walden, 2000). Summing up these 1 min fluxes to the typical EC averaging interval of 30 min, the results of both EC and wavelet method must be equal as long as the lowest contributing periods < 30 min. That is the case during steady-state conditions (Foken and Wichura, 1996; Foken et al., 2004, 2012) and Schaller et al. (2017) could prove that comparing both wavelet analysis and EC.

In the case of non steady-state conditions with contributing periods > 30 min, the EC quality control tests should flag those cases to be excluded (Foken et al., 2012). Additionally, in those cases also the ogive test (Desjardins et al., 1989; Foken et al., 1995; Oncley et al., 1990) yields contributions to the flux for periods > 30 min. Besides that, the Mexican hat wavelet will yield nonetheless in every case correct and trustworthy fluxes, also for periods > 30 min, if the integration interval in the period domain is chosen big enough (Percival and Walden, 2000; Torrence and Compo, 1998).

We will add this information to the revised manuscript and modify the mentioned sentence.

9. Page 4, line 22 What do you mean by "exact" fluxes?

The term "exact flux" in this context means that the result obtained by wavelet analysis offers an excellent resolution of the flux in time and frequency domain, depending on the chosen wavelet. **We will revise this sentence.**

10. Page 4, line 22 You mention the 1-min resolution of the flux results. But what is the limit for the time resolution of wavelet flux calculations? Why can you not resolve 1 sec, for example?

Please see the first paragraph of our answer to your comment 9. The maximum possible time resolution is restricted by the length of the timeseries and the cone of influence. Concerning the minimum resolution, we followed already available studies, because the exact calculation of the wavelet coefficients requires a certain number of values. A study on the lower limit of the resolution in time would be a specific mathematical study.

11. Page 4, line 25 Is the Morlet wavelet you used a real or complex function? I'm asking because I think in the PyWavelets Python package, the "Morlet" wavelet is real-valued, which might be unexpected. At the same time, a real-valued wavelet might have the advantage that you can show the flux direction (uptake/release) in your cross-scalograms (cf. Figure 3).

In our calculations we use the complex valued Morlet wavelet, but nonetheless the cross-wavelet scalogram only shows the real part of the complex number, which is also used by our flux calculations. As we will remove the Morlet wavelet investigations (see our answer to your general comment 1) from the revised manuscript, changes in our manuscript concerning this comment are not necessary.

12. Page 6, line 16 Here you mention that some event-minutes needed to be manually added. Later, in the last sentence of section 3.1, you describe the MAD test as a robust estimator. I wouldn't expect a robust test to need manual intervention.

Yes, the MAD test in general is a robust estimator for outliers / extreme values, but for some of the detected events, the method did not mark all non-extreme parts of the coherent event completely. In those cases we have made an additional visual inspection. **We will change the sentence to clarify that.**

13. Page 7, line 24 You explain the large difference between the two towers by the percentage of outliers. But what is the explanation for this difference in outliers? Could the real explanation be that tower 1's footprint was artificially drained?

In this section of our manuscript we refer to the statistics of detected events, i.e., the number of detected event-minutes. The statistics is based on the result of wavelet analysis, i.e., the 1-min Mexican hat wavelet flux.
At tower 1 7.7 % of all data were out of the range from Q_1-1.5(Q_3-Q_1) to Q_3+1.5(Q_3-Q_1), where Q_1 denotes the 25%- quantile and Q_3 denotes the 75%- quantile. At tower 2 5.4 % of the data are out of this range, i.e., 2.3 % less "outliers" than at tower 1.
As the MAD test is a robust estimator, it is quite resilient against such outliers. In consequence, due to the statistical properties of the data, the number of outliers (event minutes) detected by the MAD test is greater at tower 1. **We will modify the text in lines 24 – 27 to clarify that.**

Seen from ecology, the artifical drainage also has an impact on the measured flux, which leads to a reduction of the CH_4 emissions (Kittler et al., 2017). So the median flux at tower 1 (drained, 0.17 nmol mol^{-1} m s^{-1}) was significantly smaller than at tower 2 (undrained, 0.60 nmol mol^{-1} m s^{-1}). On the other hand, as written in our manuscript, the percentage of values exceeding the interquartile range by at least 1.5 times was 2.3 % (tower 1: 7.7 %, tower 2: 5.4 %). There are some possible explanations, but is difficult to prove them: 1) during stable or neutral stratification, advective processes transport methane from outside the drainage ditch into the footprint, which leads to a substantial increase of the CH_4 concentration. When flushing these accumulated CH_4 from the ground to the sensors, greater fluxes are caused, relatively to tower 2. 2) The drainage works quite good and generally lowers the water table up to 0.3 m in summer (Kittler et al., 2016; Kwon et al., 2017, 2016), but there are still some smaller patches within the drainage ditch and the footprint, where the water table was near the ground level. There the rate of methanogenesis might be greater than in other parts of the footprint, where it decreased. In times, where the footprint covers these wet patches, the flux might be greater in comparison to other wind directions. **In our manuscript, we did not include these ideas, because we could not prove them, so they are somehow speculative.**

14. Page 7, line 28 Here you describe the event seasonality, and I think it would be nice to see a plot of the event-percentages over time. You can show the three classes of events as separate lines, and the two towers as separate subplots. Maybe you can even add another subplot with the friction velocity.

As mentioned above, this paper exclusively focuses on the capability of our wavelet-based flux processing tool to detect and characterize events. Long-term statistics on event occurrence, including their net implication for the calculation of flux budgets, will be referred to the follow up paper mentioned before. We agree with the reviewer that it is somewhat disappointing to exclude the ecological implications of these event fluxes entirely within the context of this manuscript; however, we already know that those statistics cannot be explained with a short additional paragraph, so their proper interpretation would clearly exceed the appropriate length of this manuscript.

15. Page 8, line 16 How did you quantify or identify a trend?

In the context of p. 8, l. 16, "trend" just means that the values monotonically decrease, i.e. there is always are smaller value following the current value. Maybe, the word "trend" misleads the reader here, who might think that there is some kind of statistical trend modelling behind. **We will change this sentence and remove the word "trend" here.**

16. Page 9, line 34 I think it would be worthwhile to check if there is a relation between the length of the calm period preceding an event and the event's total emission. This test could give you a needed insight to separate local emissions from horizontal advection.

We had a look into this while developing the results for the original manuscript, but didn't find any conclusive correlation that would be worth to include into the paper.

17. Page 10, lines 14f If an extension of the upper period limit changes the flux so much, does this mean there is no co-spectral gap? How does this problem look like during well-mixed, stationary conditions? Have you looked at the ordinary co-spectrum and ogive?

The Morlet cross-scalogram, which allows a high resolution in the frequency domain, does not show any signs of a cospectral gap (Fig. 5 of the original manuscript, bottom panel).
During well-mixed, stationary conditions, there are no significant differences observable between the flux for an upper period limit of each 30 min and 190 min, there is a co-spectral gap. Also ogive analysis supports the finding, that there are no flux contributions for periods > 30 min.
It should be noted that in most cases the error of the EC method and the additional flux contribution after calculating the ogives doesn't show significant differences (Charuchittipan et al., 2014).

18. Page 11, lines 4f Wouldn't the regular EC processing filter out and gap-fill this period? If so, it doesn't seem right to say "regular EC data processing yielded biased results". And have you checked that the momentum flux is downwards for all these events you discuss here?

Yes, usually those times should not pass the tests on steady-state and/or turbulent conditions, so those times were filtered out. **We will change this sentence to clarify that.**
Under low wind velocities it is a difficult problem to identify if the momentum flux is upward or downward. The reason are flow distortion effects, as studied e.g. by Li et al. (2013).

19. Page 11, lines 19ff This whole paragraph hits the nail on the head. You should focus on this finding in your abstract, instead of ebullition, which you probably didn't observe.

We will revise the abstract, so that ebullition does not play a dominant role any more and change the focus more to non-turbulent mixing.

20. Page 14, line 20 Isn't it more the time since decoupling that determines how much methane can have accumulated, rather than the time since the last event?

Yes, the time since decoupling should be the most important parameter, together with the time since the last event. We will add this to the manuscript.

21. Page 15, lines 5f Methane budgets with the ecosystem as a reference should not include such high-flux events, because the ecosystem did not emit these large amounts of methane in this period. So I fail to see that filtering and gap-fill these periods would lead to a systematic underestimation of net emission, as you state here.

Yes, we definitely agree if you refer to advection as source for the measured event. The paragraph including p. 15, l. 5f starts on p. 14, l. 33 saying "In the absence of advection...". **To clarify for the reader that also the statement in p. 15, l. 5f is made under that assumption, we include "...provided that the event was not caused by advection..." into the sentence.** With advection being absent, the methane being vented during an event must have originated from the site itself, so these fluxes need to be included into the flux budget. Assuming rather constant local emissions, this would imply the tower 'sees' low-biased fluxes for a while before the event occurs, then the 'missing' methane is vented out at the onset of turbulence. Accordingly, filtering out the event would mean missing an important part of the long-term flux budget, even though not all the methane was produced at the time of venting.

22. Page 16, line 1 Why was this classification not possible here?

Your question is quite similar to the specific comment on p. 16 l 1-2 by Anonymous Referee #2. We answer both as follows: We decided to postpone this analysis to a follow-up study, because the complete, detailed investigation would be beyond the scope of this manuscript. It is quite difficult and due to the lack of additional boundary layer measurements maybe even impossible to get reliable evidence on the exact meso-scale processes triggering these events. Another major reason for our decision to exclude these events is the scope of the manuscript, which focuses on events that occur at short time scales, i.e., last only for minutes or some tens of minutes. **We agree, that these reasons were not stated clearly yet, and we will modify section 4.1.2 to make clear why the analysis might be possible, but is beyond our scope.**

23. Page 16, line 7 I'm not sure EC really "failed to resolve the events correctly". It is not designed to resolve them in the first place.

The EC method failed to resolve the events correctly, because it is not able to do that from design. **We will modify this sentence to clarify that.**

24. Page 16, line 16 How did you rule out sudden sources from the soil?

All of the observed events were triggered by meso-scale processes, mostly under stable or neutral stratification. Here the emitted methane was accumulated near the ground over longer times before the event started. During the occurrence of the meso-scale process, the accumulated methane was flushed up to the inlet of the measuring system tube causing the event flux. A differentiation whether the gas was accumulated over a longer time (very likely) or suddenly released directly from the soil, is difficult. If it is a sudden release directly from soil, it is quite unlikely that it mostly happens during stable or neutral stratification as in our study.

25. Page 24, Figure 2 Your w-measurements seem to have a mean value of about 0.1 m/s, so this is data before the tilt correction? But your wavelet cross-scalograms use w after the tilt correction, right?

Anonymous Reviewer #2 also addressed this topic in his general comment #4. So we answer both your and his question as follows: Due to a sloped terrain, a non-exact alignment of the sonic anemometer or flow distortion effects, the streamlines of the wind might be tilted. In this case, usually a coordinate rotation is conducted to move the coordinate system into the streamlines and to solve this problem. For our study, we carefully inspected the measured wind vectors during times with well-developed turbulence and good flow conditions, i.e., sufficiently high wind velocities. We could not detect any disturbance of the streamlines due to the terrain or other influences, i.e., we are sure that the assumption of a negligible mean vertical wind component (<w> = 0) is valid. Due to that finding, the complete study is based on w-data without tilt correction.
Especially due to the fact that the found phenomena were connected to a distinct vertical wind component, double rotation might lead to irregularly high rotation angles (this was investigated in an master thesis by Matthias Mauder in 2002 for the EBEX-2000 experiment, flat terrain). Instead, planar fitting (Wilczak et al., 2001) is a proper choice in such situations, since here the rotation angles are based on a long term averaging period, so that short time periods, where <w> ≠ 0, does not affect them. In our study we still did not apply planar fitting, because 1) it is not a long term study to make a careful analysis of the optimal interval for planar-fit rotation (Siebicke et al., 2012) and 2) at our towers fortunately the assumption of <w> = 0 was proven as valid for well-developed turbulence. **We will add this information to the revised manuscript.**

26. Page 25, Figure 3 The cross-scalograms don't seem to show a co-spectral peak, or an intensity decrease at the lowest and highest frequencies. Is this expected? Are these coefficients pre-multiplied by the frequency? Maybe a legend would help to read these plots. And did you define ITC and RNcov anywhere?

A co-spectral peak is not expected / visible in the cross-scalograms of this case study due to existent flux contributing periods > 30 min, which were shown in Fig. 5, where the upper period limit was set to 184 min.
The coefficients shown in all figures are not pre-multiplied by the frequency and show directly the wavelet coefficients. **We will change the colours of the plot, to make it possible to see directly the sign, i.e., the direction of flux.**
ITC and RNCov describe the integral turbulence characteristics and the steady state parameter, respectively (Foken et al., 2012). Both are very common and very well known in the EC community, so we did not define them in our manuscript.
We will remove the panel for ITC in both Figures 3 and 4, because ITC < 30 % was never reached in that time.

Technical corrections:
Thanks for your correction remarks, we will consider them in the revised manuscript.

Page 4, line 28 Missing full stop.
Page 8, line 22 You probably mean +0.67 % min-1
Page 10, line 5 Please add units to the fluxes given in parentheses

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Answer to Anonymous Referee #2

The comments of the reviewer are in black, our reply is coloured blue.

This manuscript presents an analysis of methane (CH4) eddy covariance (EC) data measured above a wetland in NE Siberia. The manuscript focuses on CH4 fluxes during night time in non-turbulent and low-mixing conditions when the EC measurement level is decoupled from the surface. Wavelet methods developed in a companion paper are used to estimate fluxes with 1 min time resolution over one summer and this high frequency flux time series is used to identify and classify high CH4 flux events during the analyzed period. These events are then speculated to be linked with atmospheric mesoscale circulation taking place in these nocturnal low-mixing conditions.
However, large part of the abstract, introduction and some other sections are discussing ebullition and other non-related topics, whereas results and conclusions are all about nocturnal low-mixing conditions. The authors should modify the beginning of the manuscript so that it matches with the end, so that the text forms one coherent entity. There are also other shortcomings in the text and description of data processing. Please see below.

As it stands the manuscript is interesting and shows promise but requires major revisions (see below) before publication. Once revised, it should be of interest also for the wider community working with micrometeorological flux measurements and hence the study is within the scope of ACP. Besides the shortcomings mentioned above, the presentation quality is good, although some figures need adjustment. I recommend the publication of this manuscript after major revision based on the comments below.

We thank Anonymous Referee #2 for his constructive comments. According to his remarks we revised our manuscript as described in the following reply.

GENERAL COMMENTS
1) Please modify the abstract and introduction so that they match with the results. In my opinion these sections should be largely rewritten since now they are quite disconnected from the rest of the manuscript. The results are about gas fluxes under nocturnal low-mixing conditions and the abstract and introduction should be written about this topic, not about arctic wetland CH4 emission dynamics. As you know, these problems related to low-mixing conditions are universal, not only related to arctic wetlands.

We agree that there is some kind of disconnection between the specific process of ebullition, which is presented in abstract and introduction, and the results of our manuscript. Nonetheless we think that it is important to consider that the scientific discussion on methane emissions in Arctic permafrost wetlands mentions ebullition as an important pathway. Thus the main reason of our data analysis was to find signs of ebullition using the wavelet approach – in our case studies, we detected other reasons for all found events, but no signs of ebullition. It seems that ebullition, occurring as heterogeneous single events on the spatial scale of the EC footprint of our towers, is not detectable. We think, that this finding might be also important for the scientific community.
We will rewrite parts of abstract and introduction as requested, so that it will be clear that ebullition is not the main topic of the manuscript, but we decided not to remove our remarks on ebullition completely due to its importance in Arctic permafrost wetlands.

2) The wavelet method is presented in the manuscript as more accurate than EC and

reliable reference for the EC fluxes. This is a strong statement, which should be supported by convincing evidence. In order to make that kind of statement you should show that when the data is processed using standard EC methodologies spurious data points are left in the flux time series, yet with the wavelet methods these problematic periods are handled better. I suspect that most of the low-mixing conditions would have been filtered out by quality screening and friction velocity filtering the data. Hence CH4 budgets derived using standard EC processing are likely not affected by these spurious fluxes during low-mixing. Please show a comparison of fluxes (e.g. monthly CH4 budgets) derived with standard EC processing (including quality screening and friction velocity filtering) and fluxes calculated with your wavelet methods to support your statement. Alternatively, you should phrase the text differently so that it is clear for the reader that it is not possible to say that the wavelet method is more accurate or reliable than standard EC.

Your question is quite similar to specific comment 8 by Norbert Pirk. Thus, we answer both as follows: using a mother wavelet with an exact resolution in time domain like the Mexican hat wavelet yields the exact flux by integrating over a short time interval, e.g., 1 min. In this case also all parts in the frequency domain that contribute to the flux are included and considered (Percival and Walden, 2000). Summing up these 1 min fluxes to the typical EC averaging interval of 30 min, the results of both EC and wavelet method must be equal as long as the lowest contributing periods < 30 min. That is the case during steady-state conditions (Foken and Wichura, 1996; Foken et al., 2004, 2012) and Schaller et al. (2017) could prove that comparing both wavelet analysis and EC.

In the case of non steady-state conditions with contributing periods > 30 min, the EC quality control tests should flag those cases to be excluded (Foken et al., 2012). Additionally, in those cases also the ogive test (Desjardins et al., 1989; Foken et al., 1995; Oncley et al., 1990) yields contributions to the flux for periods > 30 min. Besides that, the Mexican hat wavelet will yield nonetheless in every case correct and trustworthy fluxes, also for periods > 30 min, if the integration interval in the period domain is chosen big enough (Percival and Walden, 2000; Torrence and Compo, 1998).

We will add this information to the revised manuscript.

As you correctly mention, the event cases in our study would be excluded and/or replaced most probably during the gap filling analysis due to poor quality flags or the friction velocity u* being too low. Usually, gap filling algorithms determine the regression by binning the data into classes and calculating the median. This procedure leads to an exclusion of “outliers” containing very big or very small fluxes – and especially these usually rejected “outliers” which might contain distinctive, significant fluxes are targeted in our manuscript. There are a few phenomena that could explain such processes, like ebullition, free or wet convection, low level jets, breaking gravity waves or advection during calm wind, which have partly also been addressed in previous single studies.

Our manuscript explicitly investigates single events that would usually be removed by gap-filling algorithms, but does not target long-term results. A long-term study using EC on our dataset was already published by Kittler et al. (2017). An extension of our manuscript by long-term studies on the wavelet flux including error analysis would be beyond the scope of this article. Nonetheless, we definitely agree that a comparison of wavelet fluxes and EC fluxes as well as EC gap filling approaches over a longer period should be performed to quantify its effect-term balances. This would be an interesting additional future paper, which is already in preparation in our working group. **We will add this information to the revised manuscript.**

3) In many occasions the observed high flux events are linked with mesoscale motions (gravity waves, low-level jets etc.), yet the connections are quite speculative. This is understandable since these mesoscale motions are difficult to quantify with just one flux tower and the authors also clearly state this in the discussion section of the manuscript. However in contrast to the discussion, the abstract and the conclusions are written in such way that the connections are obvious based on the data. Please rephrase the text so that it is clear for the reader that the role of mesoscale motions is quite speculative and additional instrumentation would be needed for a proper identification of these flow patterns.

Yes, we generally agree that it is difficult to link the found high flux events to the identified mesoscale processes. Your question is similar to specific comment 7 by reviewer Norbert Pirk, which we both answer as follows:

Based on our meteorological measurements, we conclude that the identified mesoscale processes triggered the observed high-flux events. We agree that it is somehow “a stretch” or “speculative”, to identify these mesoscale phenomena without measurements of spatial (vertical / horizontal) profiles. Usually, periods consisting of phenomena like the found mesoscale processes, are replaced by gap filling algorithms during the standard eddy covariance processing. Long-term measurements of the atmospheric boundary layer, including devices like SODAR-RASS or LIDAR as well as arrays of other vertical / horizontal gradient measurements, could fill this gap. Long-term measurements are necessary here, because these phenomena are not detected very often and any statistical analysis is nearly impossible then.

Nonetheless we think, that it will be worth to publish observations of such relatively rare phenomena if it is possible to observe them. The detection, identification and differentiation of such mesoscale phenomena require considerable experience. Such experience is fortunately available in our working group, considering, e.g., the publications by Foken et al., (2012) or Serafimovich et al. (2018), where surface flux measurements and boundary-layer measurements were available. Of course, we carefully discussed the identified processes within our working group, to be as sure as possible in our statements regarding the available data. For the identification of these mesoscale processes we used the data from both towers (distance: 600 m). Here it is important to know that the identified phenomena are always visible at both tower 1 and 2, which supports our findings. **This was mentioned in the manuscript only in the first sentence of section 3.3, so we will add this finding also to the conclusion to highlight it.**

To sum up, the classification of the different mesoscale processes is not completely satisfying, but also not fully speculative. **We will carefully revise the manuscript, so that it is clear for the reader why the identification is not just speculative.**

4) More details about data processing are needed. Did you do coordinate rotation and how did you do it? The regular 2D-coordinate rotation (align u with mean wind and nullify mean w for each 30 min period) does not necessarily work well during low-turbulence since mean w is not necessarily zero when mesoscale motions are at play. Hence I hope that you used planar fitting (Wilczak et al., 2001) and defined the plane used in the coordinate rotation using high quality data. On the other hand if you did not do any coordinate rotation (like in Schaller et al., 2017) then the fluxes might be seriously compromised, since sonic anemometers are always slightly tilted no matter how carefully they are aligned with the surface below. Also did you correct for the time lag between gas analyzer data and sonic data? Lag time determination is always difficult for periods with low and intermittent turbulence. Therefore, please

provide additional details about EC processing. Related to the wavelet analysis, how did you take into account the time series edges and their effect on the results? Did you zero-pad the data and then estimate the cone of influence (Torrence and Compo, 1998)? This is important especially for the low frequencies. Please add details, since they are missing also from the companion paper (Schaller et al., 2017). As it is, it is difficult to judge whether the data were processed in a proper way.

Thanks for addressing these important points, we agree that in the current state of the manuscript it is difficult to be sure that the data (pre-) processing was done in a completely correct way, so we will add these information as follows.

<u>Coordinate rotation</u> – Norbert Pirk also addressed this topic in his specific comment #25. So we answer both your and his question as follows: Due to a sloped terrain, a non-exact alignment of the sonic anemometer or flow distortion effects, the streamlines of the wind might be tilted. In this case, usually a coordinate rotation is conducted to move the coordinate system into the streamlines and to solve this problem. For our study, we carefully inspected the measured wind vectors during times with well-developed turbulence and good flow conditions, i.e., sufficiently high wind velocities. We could not detect any disturbance of the streamlines due to the terrain or other influences, i.e., we are sure that the assumption of a negligible mean vertical wind component (<w> = 0) is valid. Due to that finding, the complete study is based on w-data without tilt correction.
Especially due to the fact that the found phenomena were connected to a distinct vertical wind component, double rotation might lead to irregularly high rotation angles (this was investigated in an master thesis by Matthias Mauder in 2002 for the EBEX-2000 experiment, flat terrain). Instead, planar fitting (Wilczak et al., 2001) is a proper choice in such situations, since here the rotation angles are based on a long term averaging period, so that short time periods, where <w> ≠ 0, does not affect them. In our study we still did not apply planar fitting, because 1) it is not a long term study to make a careful analysis of the optimal interval for planar-fit rotation (Siebicke et al., 2012) and 2) at our towers fortunately the assumption of <w> = 0 was proven as valid for well-developed turbulence. **We will add this information to the revised manuscript.**

<u>Time lag correction</u> – the time lag correction between the sonic anemometer and the gas analyser was conducted by maximisation of the covariances by cross correlation for every 30-minutes-interval. Because of the conditions with low turbulence the time lag may be different for each time series. No constant time lag was applied. **We will add this information to the revised manuscript.**

<u>Edge effects in wavelet analysis</u> – the filtering of erroneous results of the wavelet calculations at the beginning and end of the cross scalogram is of crucial importance to obtain results of high quality without border effects (Torrence and Compo, 1998). Our wavelet analysis was conducted on the whole available dataset from 1st June to 15th September 2014 using a windowed approach. For the Mexican hat wavelet, the lag between two subsequent window calculation start points was set to 6 hours while the length of each calculated window was 12 hours, i.e., it overlaps the window start/end points. The data was zero-padded and the cone of influence estimated. At the end, the calculated windows were cut at the borders and merged, so that border effects in the final result only occur at the beginning and end of the whole time series. These border times were excluded from further analysis. **We will add this information to the revised manuscript.**

SPECIFIC COMMENTS

page 7, line 24-27 This part is unclear. Do you mean extreme outliers in the 20 Hz data or in the 1-min flux data? It is difficult to understand why the outliers could explain the difference in the amount of events observed with the two towers. Please clarify and rephrase.

In this section of our manuscript we refer to the statistics of detected events, i.e., the number of detected event-minutes. The statistics is based on the result of wavelet analysis, i.e., the 1-min Mexican hat wavelet flux.
At tower 1 7.7 % of all data were out of the range from Q_1-1.5(Q_3-Q_1) to Q_3+1.5(Q_3-Q_1), where Q_1 denotes the 25%- quantile and Q_3 denotes the 75%- quantile. At tower 2 5.4 % of the data are out of this range, i.e., 2.3 % less “outliers” than at tower 1.
As the MAD test is a robust estimator, it is quite resilient against such outliers. In consequence, due to the statistical properties of the data, the number of outliers (event minutes) detected by the MAD test is greater at tower 1. **We will modify the text in lines 24 – 27 to clarify that.**

Sect. 3.3 I would like to see an analysis using Richardson number (Ri), since Ri is typically used to indicate dynamic stability of the flow. Moreover, if Ri exceeds so called critical Richardson number (Ric) then the turbulence is strongly dampened or even almost completely wiped out (e.g. Grachev et al., 2013). Ric is typically said to be around 0.25, although this is debated (Galperin et al., 2007). It would be interesting to see how Ri is affected by these events you identified and if Ri>Ric always before the events. The analysis you did on stability parameter (z/L) is somewhat similar, however I would prefer Ri since you cannot determine a turbulence cutoff with z/L the same way as with Ri. I suggest you use gradient Richardson number for the analysis, however in case you are missing the needed vertical gradients, then use flux Richardson number.

The flux Richardson number (Rf) can be converted exactly into z/L (e.g., Arya, 2001; Foken, 2017); the gradient Richardson number should not be used under stable conditions because of possible decoupling between the both measurement heights. It can be assumed that the critical Richardson number is approximately equal to z/L=–1. The calculation for Rf and z/L is extremely affected by errors because for stable conditions u or u* are near zero, and small errors can generate large effects on the stability parameter. For the accuracy under such conditions see also Högström (1996). Additionally, in our studies we use z/L only as a general classifier for the stability, i.e., the exact numerical values should not have an important impact on our findings.

p. 8, l. 20-25 Why the analysis with relative humidity? I would guess that it is not relevant for the topics at hand.

Especially ecologists use the relative humidity (combined with air temperature) quite often for studies on atmosphere-biosphere exchange. We think that the information on humidity provides meaningful information that should remain in the manuscript.

p. 8, l. 29-32 Referring to my comment before, did you do coordinate rotation? It should be always done, regardless of how flat the terrain is since anemometers are always at least slightly tilted. If coordinate rotation is not done, then w data is compromised by horizontal wind speed fluctuations.

Please see our answer to your general comment 4).

p. 9, l. 6-8 It is difficult to understand why there would be unstable stratification during night. Could it be because during these events EC is not working properly and hence you have erroneous heat fluxes and therefore also erroneous values for z/L? Did you have also negative vertical gradients in air temperature (decrease with height) during these periods?

We agree that usually during times with short-wave incoming radiation ≈ 0 unstable stratification is quite unlikely to happen. In the high-latitude Arctic zone (68.78° N), depending on the date, there are just about a few hours between sunset and sunrise. In our study, we defined "night" by the fixed time span 21:00 to 9:00. **We will add this information to the revised manuscript.**

Additionally, we revisited all events that occurred during our fixed nighttime span 21:00 to 9:00. Unstable stratification was observed only in times where also short-wave incoming radiation > 20 Wm^{-2} was measured. In such cases it is not unlikely to observe at least slightly unstable situations. **We will add this information to the revised manuscript.**

p. 9 l. 16 This title should be modified. Based on the evidence shown it is not possible to say that there was advection of CH4 to the study domain. In order to make such a statement you should have measured also CH4 concentration horizontal gradients.

Please see in general our answer to your general comment 3, where we show why our statements on the mesoscale processes are still not completely satisfying, but definitely not fully speculative. Due to the fact that there are only rare studies on such kind of mesoscale events in the Arctic, we think that it is worth to publish them.
Specifically to your question on section 3.4 labeled "Nighttime advection": We agree, that it is much more difficult to detect advection without direct gradient profile measurements. On the other hand, Figure 6 in the manuscript supports this finding and gives evidence, because it directly shows the approaching fog bank. The occurrence and arrival of this fog bank at the towers exactly in time with the observed event in the data clearly indicates advection. Also in literature such kinds of fog events are classified directly as advection fog (e.g., Stull, 1988).

Sect. 3.4 The event that is analyzed in this section was already analyzed in the companion paper (Schaller et al., 2017). For instance Fig. 4 here is partly the same as Fig. 5 in Schaller et al. (2017) and also the text is quite similar. It would be better to concentrate on some other event in this study, now this analysis is a bit redundant.

We agree that there is a bit of redundancy between this manuscript and Schaller et al. (2017), due to the fact that the event discussed intensively in our manuscript was already shown partly there. But, the focus between the two publications is completely different: Schaller et al. (2017) show the methodology behind the wavelet flux calculation and validate the method against EC for times of well-developed turbulence and stationary conditions. In section 3.2.2 of that publication we gave a very short insight to the capability of wavelet analysis to resolve also fluxes in times, where the steady-state condition is not fulfilled. In that manuscript, we "promised" the reader that there will be a follow-up paper, which investigates such kind of events as well as this specific event in detail. We think that we should keep this "promise" we gave in our companion paper, so we decided not to change our focus to another event.
In the revised paper we will clarify that this example was analyzed in Schaller et al. (2017) **with respect to the method, while this article investigates the underlying process.**

p. 10 l. 12-15 You analyse here a period that lasts for two hours, right? Can you then extent the maximum wavelet period above 120 min? If you can, then how accurate the results are at these very low frequencies, given that your time series does not cover even one whole wavelet when the wavelet period is above 120 min? On a related note, shouldn't you also take into account the cone of influence (those regions of the wavelet spectrum that are significantly affected by the edges; see Torrence and Compo, 1998) in your cross-scalograms and in the corresponding analysis? If you used two hour long time series in this analysis, then wavelet periods above 120 min are definitely within the cone of influence and hence unreliable.

Please see our remarks on the edge effects on your general comment 4). If there are only two hours of data, a wavelet analysis on this dataset will not yield to trustworthy data of that length due to parts of the results being within the cone of influence. None of the data we used or showed in our studies are influenced by edge / border effects, as already explained. **We will add this information to the revised manuscript.**

p. 11 l. 4-5 This sentence should be modified. One cannot claim that EC fluxes were systematically overestimated since you do not have an absolutely correct reference. For instance damping of the signal within the cone of influence (Torrence and Compo, 1998) might decrease the wavelet based fluxes. This could partly explain the observed difference.

Please see our answer on your general comment 2). Due to the mathematical properties of the wavelet analysis in general the steady-state assumption has not to be fulfilled, while eddy covariance results might be significantly biased on the same time. Additionally, the chosen mother wavelet (Mexican hat) allows a very good resolution in the time domain and thus, as there is no influence by edge effects in this period, there is no damping of the signal caused by the cone of influence. **It is not possible to set up an "absolutely correct reference" under field conditions. To consider that, we remove the word "strongly" in the revised manuscript.**

p. 11 l. 31 Please replace "by an eddy-covariance system" with "with these wavelet algorithms".

Because the footprint does not depend on the data analysis we believe that "EC system" is already a more general name than "EC method" or "wavelet method". **To be sure that the reader will not misunderstand that, we changed the sentence to "by this EC setup with a sensor height ≥ 4.9 m above ground".**

Sect. 3.52 & 3.5.3 & 3.5.4 Difference between these three categories is difficult to see, especially the description of 3.5.3 and 3.5.4 looks similar. Try to emphasize more the differences in meteorological forcings between these event categories. As it reads now, combining the events with different mesoscale flow patterns seems rather subjective.

Please see our answer to your general comment 3), which also addresses the differentiation between the meteorological forcings. Concerning the mentioned sections, we carefully revisited them: the examples 3.5.1, 3.5.3, 3.5.4 look similar, but the reason is different. 3.5.1 is due to the constant wind direction and the observed fog clearly an advection situation. 3.5.3 and 3.5.4 show both an increase of turbulence, but a change of the wind direction is typical for a low level jet and not for braking gravity waves. Example 3.5.2 has all criteria for a passage of a frontal system, see e.g. pressure. After carefully revisiting the events, **we decided to keep the differentiation, also due to our answer to your general comment 3).**

p. 12 l. 12-13 As you probably know, ebullition is often hypothesized to be connected with falling (Tokida et al., 2007), but sometimes also increasing atmospheric pressure (Chen and Slater, 2015). Could this be somehow connected to this daytime event?

We thoroughly inspected the observations for that daytime event again. The course of the air pressure, which was decreasing before the event and increasing by 2 hPa/hour with and after the event clearly supports the assumption of a front passing by, which is also observable in all fluxes, not only the methane flux.

p. 13 l. 20-21 Onset of turbulent mixing in the morning has been shown to cause CH4 flux peaks also in other studies (e.g. Peltola et al., 2015). Did these events that you identified to be connected with the onset of turbulent flow take place in the morning?

All events that were determined to be caused by the onset of turbulent flow were observed during night time, but none of them in the morning. It should be noted here that due to high geographical latitudes there was never a complete sunset down to darkness and also the sunrise does not occur that rapidly as, e.g., in the middle latitudes like in Central Europe.

p. 14 l. 8 How did you define which events were influenced by advection? These periods discussed here are most likely non-stationary and would have been filtered out from standard EC data.

Please see our answer to your general comment 3). In the usual EC processing these periods would be filtered out, and subsequently treated by gap filling algorithms as they are in fact non-stationary and would fail the steady-state test.

p. 14 l. 11-18 This is a good point and it would have been nice to see this idea used in the prior analysis.

Such an analysis needs an extended experimental setup. We think that this analysis should be done using data from a long-term study including more towers, additional boundary layer measurements as well as arrays of other vertical / horizontal gradient measurements.

p. 14 l. 24 How did you determine this 15 min limit for identifying events that are affected by advection?

In fact, this limit is somehow a helpful “practical rule of thumb” for the events observed at our measuring site considering the available. On the other hand, we also see that is difficult or even impossible to specify an exact minimum event duration, where you can be sure that advection is the driver. A long-term study would be necessary to prove that, **therefore we will remove this sentence in our manuscript.**

Sect. 4.1.1 I would add here text about CH_4 concentration profiles since large part of this manuscript discusses flushing of previously stored CH_4 below the EC level. With detailed concentration profile you could measure this.

Yes, profile measurements would be definitely a good measure to support findings on meso-scale processes like in our study. In addition to our answer to your general comment 3), **we will also add this information to our manuscript.**

p. 15 l. 1-2 Why the analysis on cluster events was not possible?

We assume, you mean p. 16 l. 1-2. We decided to postpone this analysis to a follow-up study, because the complete, detailed investigation would be beyond the scope of this manuscript. It is quite difficult and due to the lack in additional boundary layer measurements maybe even impossible to get reliable evidence on the exact meso-scale processes triggering these events. Another major reason for our decision to exclude these events is the scope of the manuscript, which focuses on events that occur at short timescales, i.e., last only for minutes or some tens of minutes. **We agree, that this reasons were not stated clearly yet, so we will modify section 4.1.2, so that is clear, why the analysis might be possible but beyond the scope.**

Figure 2 Mean w is around 0.15 m/s, which is quite high value. Did you do coordinate rotation? You should definitely do it. Another thing: you could add here the Richardson number, like I suggest above.

Please see our answer on your general remark 4) and on your specific remark on section 3.3.

Figures 2 & 3 These two figures are complicated and should be explained better. For instance how did you define “Unstable”, “Stable” and “Neutral”? Where the stability is shown? How can you have EC data in the bottom plot with different quality classes at the same time?

We will improve the caption text of both figures, so that everything is well explained. For the definition of the stability we followed the recommendations on error analysis by Foken and Wichura (1996) and Foken et al. (2004, 2012) to be consistent. These recommendations derive from the fact that here the universal functions are nearly equal to 1 (Foken and Skeib, 1983). Stability was labeled “unstable” for $zL^{-1} < -0.0625$, “stable” for $zL^{-1} > 0.0625$, “neutral” for $-0.0625 \leq zL^{-1} \leq 0.0625$. In the plot the stability is shown for every 30-minute-interval directly underneath the cross-wavelet scalogram of Mexican hat.

The quality class of the EC data is labeled by small rectangles in the bottom panel of Fig. 4f for each 30 minute interval, i.e., the timestep 0:00 – 0:30 in Fig. 3 is labeled as quality class 4 – 6. There are no different quality classes at the same time, but maybe here the Figure is misleading the reader. **Therefore, we will revise the bottom planel, so that is easier to determine the EC quality class.**

Figures 2, 3 & 4 You most likely have change in flux sign at some certain color in the cross-scalograms (e.g. negative fluxes at blue colors and positive at red colors). Please highlight the zero flux lines in the cross-scalograms with e.g. white contour lines. Also, is the color scale the same in both subplots? If not, then please try to use one color scale per figure. Add also the cone of influence (Torrence and Compo, 1998) to all subplots.

Yes, the values in cross-scalogram are negative or positive valued, depending on the direction of flux. **We will change the colors in the revised manuscript, so that intensity and algebraic sign are easy to read off. Also the color scale for the subplots in Figures 2, 3 & 4 will be changed. There is no cone of influence (see your general comment 4), but we will note this in figure captions.**

TECHNICAL CORRECTIONS

p. 4, l. 12 You defined the abbreviation EC here, but you defined it already on page 2 line 19. Use the abbreviation everywhere in the text after you define it. Also, you use both “eddy covariance” and “eddy-covariance”, replace both with EC.

We will change that.

p. 7, l. 14 and other places Please give dates in a consistent manner and try to follow the journal recommendations.

We will change that.

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List of relevant changes made in the manuscript

Note: only changes that lead to a relevant change in comparison to the initial submission are listed. Minor changes that do not change the findings were not listed.

p. 1, Abstract: moved focus from ebullition to episodic outbursts of methane in general

p. 1ff: moved focus from ebullition to episodic outbursts of methane in general

p. 3, l. 21: inserted recently published work by Iwata et al. (2018), who successfully used our wavelet method and compared it to their own method

p. 4, l. 6f: replaced „a.sl.“ by „above ground“ for the observation height of the towers

p. 4, l. 19 – 22: added information on coordinate rotation

p. 5, l. 3 – 15: provided detailed information on wavelet processing and the choice of the Mexican hat wavelet

p. 8, l. 7 – 12: improved explanation on outlier statistics

p. 9, l. 24 – 30: added z/L thresholds for stability of atmospheric stratification, added reason for occurrence of unstable conditions during nighttime (21:00 – 9:00)

p. 10, l. 5 – 11: added information about the link of the case study to the companion paper in AMT.

p. 10., l. 28 – p. 11, l. 14: removed all information concerning Morlet wavelet results.

p. 16, l. 13 – 20: improved explanation why cluster events analysis was beyond the scope

p. 16, l. 24 – 26: emphasized that all events were found simultaneously at both towers, which strongly suggests the influence of mesoscale triggers.

p. 26f, Fig. 3ff: new colors for wavelet cross scalograms allow to see easily the direction of flux.

Characterisation of short-term extreme methane fluxes related to non-turbulent mixing above an Arctic permafrost ecosystem

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Abstract. Methane (CH_4) emissions from biogenic sources, such as Arctic permafrost wetlands, are associated with large uncertainties because of the high variability of fluxes in both space and time. This variability poses a challenge to monitoring CH_4 fluxes with the eddy covariance (EC) technique, because this approach requires stationary signals from spatially homogeneous sources. Episodic outbursts of CH_4 emissions, i.e. ~~outgassing in the form of bubbles from oversaturated groundwater or surfacewater~~triggered by spontaneous outgassing of bubbles or venting of methane-rich air from lower levels due to shifts in atmospheric conditions, are particularly challenging to quantify. Such events typically last for only a few minutes, which is much shorter than the common averaging interval for ~~eddy covariance~~ EC (30 minutes). The steady state assumption is jeopardized, which potentially leads to a non-negligible bias in the CH_4 flux. ~~We~~ Based on data from Chersky, NE Siberia, we tested and evaluated a flux calculation method based on wavelet analysis, which, in contrast to regular EC data processing, does not require steady-state conditions and is allowed to obtain fluxes over averaging periods as short as 1 minute. ~~We demonstrate that the occurrence of extreme CH_4 flux events over the summer season followed a seasonal course with a maximum in early August, which is strongly correlated with the maximum soil temperature.~~ Statistics on meteorological conditions before, during, and after the detected events revealed that it is atmospheric mixing that triggered such events rather than CH_4 emission from the soil. By investigating individual events in more detail, we identified a potential influence of various mesoscale processes like gravity waves, low-level jets, weather fronts passing the site, and cold-air advection from a nearby mountain ridge as the dominating processes. The occurrence of extreme CH_4 flux events over the summer season followed a seasonal course with a maximum in early August, which is strongly correlated with the maximum soil temperature. Overall, our findings demonstrate that wavelet analysis is a powerful method for resolving highly variable flux events on the order of minutes~~. It is a reliable reference to evaluate the quality of EC fluxes~~ , and can therefore support the evaluation of EC flux data quality under non-steady-state conditions.

1 Introduction

Methane (CH_4) is one of the most important greenhouse gases (Saunois et al., 2016b), but unexpected changes in atmospheric CH_4 budgets over the past decade emphasise that many aspects regarding the role of this gas in the global climate system remain unexplained to date (e.g. Saunois et al., 2016a; Nisbet et al., 2016; Schwietzke et al., 2016; Schaefer et al., 2016). Atmospheric CH_4 increased in concentration from 722 ppb in the year 1850, i.e. before industrialisation started, to 1810 ppb in the year 2012 (Hartmann et al., 2013; Saunois et al., 2016a). Current concentration levels are the highest reached in 800,000 years (Masson-Delmotte et al., 2013), and emissions and concentrations are likely to continue increasing, making CH_4 the second most important greenhouse gas (after CO_2) that is strongly influenced by anthropogenic emissions (Ciais et al., 2013; Saunois et al., 2016b). In comparison to CO_2, CH_4 is characterised by a shorter atmospheric lifetime and a higher warming potential (34 times greater, referring to a period of 100 years and including feedbacks; Myhre et al., 2013). With management of CH_4 emissions being identified as a realistic pathway to mitigate climate change effects (Saunois et al., 2016a), quantitative and qualitative insights into processes governing CH_4 sources and sinks need to be improved in order to better predict its future feedback with a changing climate.

The Arctic has been identified as a potential future hotspot for global CH_4 emissions (Zona et al., 2016), but the effective impact of rapid climate change on the mobilisation of the enormous carbon reservoir currently stored in northern high latitude permafrost soils remains unclear (e.g. Sweeney et al., 2016; Parazoo et al., 2016; Shakhova et al., 2013; Berchet et al., 2016). Under warmer future conditions, increased thaw depths in Arctic permafrost soils as well as geomorphologic processes such as thermokarst lake formation are expected to mobilise carbon pools from deeper layers (Fisher et al., 2016), while at the same time the activity of methanogenic microorganisms may be promoted. Both factors would contribute to a potential increase in CH_4 emissions from permafrost wetlands (Tan and Zhuang, 2015). However, complex feedback mechanisms between climate change, hydrology, vegetation and microbial communities may partly counterbalance these increased emissions (Kwon et al., 2017; Cooper et al., 2017). In order to improve the reliability of simulated Arctic CH_4 emissions under future climate scenarios, several process-based modeling frameworks for predicting CH_4 emissions have been improved in the last years (Kaiser et al., 2017; Raivonen et al., 2017), but the confidence in the results remains low, which can also be attributed to a lack of high quality observational data sets for CH_4 emissions from Arctic permafrost wetlands (Ciais et al., 2013).

The eddy covariance (EC) method allows for accurate and continuous flux measurements at the ecosystem scale, but strict theoretic assumptions need to be fulfilled to ensure high-quality observations. Besides the requirement of steady-state conditions and a fully developed turbulent flow field (Foken and Wichura, 1996), the observation of CH_4 fluxes in high latitudes require some special considerations. These include technical challenges related to harsh climate conditions in remote areas of the high northern latitudes (Goodrich et al., 2016), and also problems related to atmospheric phenomena such as very stable stratification that inhibits turbulent exchange during polar winter. Methodological difficulties specific to CH_4 also play a role: since net CH_4 emissions are not only dependent on the production conditions for CH_4 in the soil, but also on the transport processes from soil to atmosphere, they are characterised by higher temporal variability, compared to CO_2. CH_4 release through ebullition (Peltola et al., 2017; Hoffmann et al., 2017), i.e. episodic outgassing in the form of bubbles, typically occurs in events of only a few minutes in length, much shorter than the common averaging interval for EC (30 minutes). CH_4 ebullition events ~~thus~~ that simultaneously occur within large fractions of the tower footprint thus hold the potential to violate the steady state assumption for EC~~, with the potential to systematically bias~~ . Also, continuous emissions may lead to the accumulation of methane pools close to the ground during periods of very stable stratification, and their instantaneous venting towards higher levels linked to changes in atmospheric conditions may cause pronounced spikes in the signal that violate the EC assumptions. Both cases would lead to systematic biases in EC flux calculations because of an incorrect Reynolds decomposition. As a consequence, high emission events are likely to be discarded from the time series as very low quality data, or outliers, which has the potential to systematically underestimate long-term CH_4 budgets (Wik et al., 2013; Bastviken et al., 2011; Glaser et al., 2004).

To constrain potential systematic biases in EC data that are related to the afore-mentioned effects, a direct comparison with other observation techniques such as ecosystem chambers can be used. Experiments involving parallel observations with both approaches have been conducted (e.g. McEwing et al., 2015; Emmerton et al., 2014; Sachs et al., 2010; Merbold et al., 2009; Corradi et al., 2005). Chamber measurements are capable of resolving small-scale CH_4 emissions properly, but in most cases they cover only a small area on the order of up to a few m^2. Furthermore the installation of the chamber as well as its operation could introduce disturbances to the study area, which might lead to biased results. Upscaling approaches from the chamber to the EC footprint scale already exist (e.g. Zhang et al., 2012), but until now no method has been presented that aims to calculate of CH_4 fluxes directly from high frequency EC measurements~~, including consideration of ebullition~~.

As a second approach to evaluate potential systematic biases in ~~eddy-covariance~~ EC CH_4 fluxes, a different calculation method can be applied to high frequency atmospheric observations that does not require the theoretic assumptions that limit the applicability of EC (Schaller et al., 2017b). Wavelet analyses provide this option (e.g. Collineau and Brunet, 1993a; Katul and Parlange, 1995), since they can be applied to calculate fluxes for time windows smaller than 10 to 30 min due to wavelet decomposition in time and frequency domain without ignoring flux contributions in the low-frequency range. Moreover, wavelet transformation does not require steady-state conditions (Trevino and Andreas, 1996) but can also be applied on time series containing non-stationary power (e.g. Terradellas et al., 2001). As a drawback, the calculation of fluxes using wavelet transform requires considerably more computational resources even when a windowed approach is used.

The focus of the present study is on the interpretation of CH_4 emission events detected by a wavelet software package (Schaller et al., 2017b, a), which has already successfully been applied to the non-steady state fluxes during a solar eclipse (Schulz et al., 2017) or to CH_4 fluxes from a shallow lake containing ebullition (Iwata et al., 2018). This approach, which builds on the raw data sampled by EC towers, allows us to resolve fluxes not only over 30 minute averaging periods, but also for an averaging interval of 1 minute. Such a higher temporal resolution facilitates detection of the exact time and duration of non-stationary CH_4 release events. The obtained results can be directly compared against EC fluxes, where a good agreement has been shown for times with well-developed turbulence conditions. We present an analysis of whether peak CH_4 emission events at timescales on the order of minutes ~~– triggered e.g. by ebullition –~~ can be found in the results, what their basic characteristics are, and how these events may influence the computation of long-term CH_4 budgets. Finally the study aims to find meteorological triggers that could cause the observed events to occur.

2 Material and methods

2.1 Study site

Field work was conducted at an observation site within the floodplain of the Kolyma River (68.78° N, 161.33° E, 6 m above sea level) situated about 15km south of the town of Chersky in Northeast Siberia (Kittler et al., 2016; Kwon et al., 2017). The site is classified as wet tussock tundra underlain by continuous permafrost, with very flat topography. Averaged over the period 1960-2009, the mean annual temperature was -11°C, and the average annual precipitation amounts to 197mm (Göckede et al., 2017).

Two ~~eddy-covariance~~ EC towers were installed in summer 2013 about 600m apart, one of them (tower 1) focusing on an artificially drained section of the tundra site, the other (tower 2) serving as a control site to monitor undisturbed conditions. Both systems were equipped with the same instrumentation setup, including a heated sonic anemometer (uSonic-3 scientific, METEK GmbH) and a closed-path gas analyser (FGGA, Los Gatos Research Inc.), and feature about the same observation height (tower 1: 4.9m ~~a.s.l.~~above ground; tower 2: 5.1m ~~a.s.l.~~above ground). Due to their proximity, both towers are also exposed to the same meteorological conditions. Inter- and Intra-annual variability of the exchange fluxes of CO_2 and CH_4, including an analysis of related environmental controls, are presented by Kittler et al. (2017b). For more details on the instrumentation setup, please refer to Kittler et al. (2016, 2017a).

2.2 Raw data processing and flux calculation

The raw data on the high-frequency fluctuations of wind and mixing ratios were collected using the software EDDYMEAS (Kolle and Rebmann, 2007) at a sampling rate of 20 Hz. Ancillary meteorological data were acquired at 1 Hz frequency through the LoggerNet software (Campbell Scientific Inc., Logan, Utah, USA) on a CR3000 Micrologger (Campbell Scientific). Both programs were running on-site on a personal computer, using the local time zone (Magadan time, UTC + 12 h). The mean local solar noon is UTC + 13 h. Within the context of this study, datasets within the period ~~1st~~01 June to 15~~th~~ September 2014 were analysed.

As a first approach to calculate turbulent CH_4 fluxes, we employed the ~~eddy-covariance (EC)~~ EC method using recent recommendations on correction methods and quality assurance measures (Aubinet et al., 2012). A coordinate rotation into the streamlines (Rebmann et al., 2012) was not applied due to the very flat and homogeneous terrain at both towers. There was no tilt in the alignment of the sonic anemometers at both towers and after a careful inspection of the raw data no disturbances of the streamlines due to the terrain or other influences could be found. This allows the assumption that $\bar{w} = 0$ for well-developed turbulence. We used the software package TK3 (Mauder and Foken, 2015a, b) for this purpose, which includes all necessary corrections, data quality tests (Foken et al., 2012a), and a spike detection test using the Median Absolute Deviation (MAD / Hoaglin et al., 2000; Mauder et al., 2013). TK3 has been demonstrated to compare well with other available packages (Mauder et al., 2008; Fratini and Mauder, 2014). As the standard for the EC method, we derived turbulent fluxes with an averaging period of 30 minutes.

Because highly non-steady state conditions were expected for CH_4 fluxes at this observation site, which pose a serious violation of the basic assumptions linked to the eddy-covariance EC method (Foken and Wichura, 1996), we applied a wavelet-based calculation method as a second flux processing approach in addition to the standard eddy-covariance EC data processing. Schaller et al. (2017b) have developed a method for wavelet-based flux computation that offers the possibility of determining exact fluxes with a user-defined time resolution that can be as low as about 1 minute. Within the context of this study, we applied their calculation tool with a continuous wavelet transform using the Mexican hat wavelet (WV_{Mh}), which provides an excellent resolution of the flux in the time domain. Our results therefore allow It should therefore be the preferred mother wavelet to obtain an exact localisation of single events in time (Collineau and Brunet, 1993b). We additionally processed the data using the Morlet wavelet (WV_M), which provides an excellent resolution in frequency but a worse resolution in time domain, compared to Mexican hat (Domingues et al., 2005). In combination with the Mexican hat wavelet, this additional information can provide additional insight into turbulent flow characteristics, and therefore a better characterization of highly non-stationary datasets without loosing information in the frequency domain (Collineau and Brunet, 1993b). For more details on the implementation of the method directly refer to Schaller et al. (2017b).

For wavelet analysis the spike-corrected (Mauder et al., 2013) raw data of both vertical wind speed w and CH_4 mixing ratio c was used. The timeseries was corrected for a time lag between these parameters by maximisation of the covariances by cross correlation for every 30-minutes interval (Rebmann et al., 2012). As also stated for EC, a coordinate rotation was not applied. The cone of influence (COI; Torrence and Compo, 1998) was estimated and all results are based on data not affected by edge effects.

For steady state conditions, the wavelet and eddy-covariance methods EC method have been shown to be in very good agreement . For more details on the implementation of the method directly refer to Schaller et al. (2017b)(Schaller et al., 2017b). In the case of non steady-state conditions with contributing periods $> 30\,\mathrm{min}$, the EC quality control tests should flag those cases to be excluded (Foken et al., 2012b). Additionally, in those cases also the ogive test (Desjardins et al., 1989; Foken et al., 1995; Oncley et al., 1990) yields contributions to the flux for periods $> 30\,\mathrm{min}$. Besides that, the Mexican hat wavelet will yield nonetheless correct and trustworthy fluxes, also for periods $> 30\,\mathrm{min}$, if the integration interval in the period domain is chosen big enough (Percival and Walden, 2000; Torrence and Compo, 1998). In this study, the upper integration limit λ_{max} in period domain was set to $33\,\mathrm{min}$. To account for low-frequency contributions in the case study in section 3.4, a second calculation was conducted, where $\lambda_{max} = 184\,\mathrm{min}$.

2.3 Detection and classification of events

2.3.1 Detection of events

While spikes within the 20 Hz raw data were already identified in the MAD-Test (Mauder et al., 2013), in a first stage of the wavelet-based event detection we conducted an additional MAD test on processed fluxes similar to Papale et al. (2006):

$$\langle d \rangle - \frac{q \cdot MAD}{0.6745} \leq d_i \leq \langle d \rangle + \frac{q \cdot MAD}{0.6745} \tag{1}$$

where

$$d_i = (x_i - x_{i-1}) - (x_{i+1} - x_i) \tag{2}$$

parameterises the difference of the current value x_i to the previous and next value in time. $\langle d \rangle$ denotes the median of all those double differenced values and

$$MAD = \langle |d_i - \langle d \rangle| \rangle \tag{3}$$

Due to its robustness the median absolute deviation is a very good measure of the variability of a time series and substantially more resilient to outliers than the standard deviation (Hoaglin et al., 2000). The test was applied to Mexican hat wavelet flux with a time step of $\Delta t = 30\,\mathrm{min}$. If a value d_i in the time series exceeded the given range in equation (1), it was detected as an event. A threshold value of $q = 6$ was found to be suitable to reliably separate events from periods with a regular exchange flux between surface and atmosphere.

The same MAD test calculations have also been applied to the flux with averaging interval $\Delta t = 1\,\mathrm{min}$. The purpose of this higher resolution analysis was first to precisely constrain the duration of an event down to the resolution of minutes, and second to allow the detection of exact start and end times of events. We defined here a minimum duration of 2 minutes for an event, since this way we could avoid labelling a sequence of high-frequency spikes, which sometimes pass the TK3 spike detection threshold, as an event.

2.3.2 Classification of events

The approach described above only detects 1-minute-steps belonging to an event, but does not provide any knowledge about typical structures of such contiguous single events. The term "structure" in this context refers to the specific sequence of consecutive 1-minute flux values that together form the event: in a simple case, flux rates regularly increase until reaching a plateau, then drop back to their starting values, with no events directly before or afterwards. More complex events appear as clusters, i.e. during a prolonged period of time several shorter events occur close to each other. Since events with different structure may also be triggered by different atmospheric conditions, we developed a basic classification to differentiate types of events consisting of adjacent 1 minute steps.

Based on the single event-minutes identified by the MAD test, a manual search for characteristic, repeating patterns within all half hour intervals that contained events resulted in the definition of three typical event structures. In this context, it was found that the MAD test for a threshold value of 4 or 6 was not always able to resolve the whole event (blue plus-sign within grey shaded event duration in Fig. 1), thus in such cases actual starting and ending time of an event were corrected manually.

We ~~labeled~~ labelled the first event type a single **peak event**. For this category, in the simplest case the flux increased monotonically up to one maximum event peak or a plateau with high flux rates, followed by a monotonic decrease back to base level. No other events were detected within 30 min before or after the single peak event. As the example (Fig. 1, top panel) shows, such an ideal sequence cannot be expected in general, but in all cases a pattern of coherent single event-minutes showing the tapering to one peak or a few subsequent local maxima clearly suggested the classification of a "peak event". Peak events can occur as either negative or positive outliers from the baseline flux. If a positive peak was followed or preceded by a negative one or vice versa, both were combined into a single "peak event" as long as the magnitude of the second peak was lower than one quarter that of the main peak.

We termed the second event class **down-up** events. Down-up events had the same basic properties as single peak events, but in contrast they consisted of one sharp negative and positive peak each, which were of similar magnitude (Fig. 1, center panel). If the order of the two peaks was reversed, the process was called an **up-down** event. Typically the two extremes within a down-up event were separated by several minutes (e.g. 4:58 and 5:01 in Fig. 1, middle), and such (non-extreme) transition periods were frequently not labelled as events by the MAD test because they did not exceed the threshold for event detection. In this case these event-minutes needed to be manually added to form a coherent down-up / up-down event.

The third class of events in our classification scheme was called **clusters**. In this category we collected all events that did not meet the criteria defined above for single peak events or down-up events, instead showeing a coherent pattern but not an unambiguous structure. This was generally the case for longer event periods that were potentially formed by the merging of several consecutive shorter events (Fig. 1, bottom panel). However, in these cases a clear distinction of individual events was impossible due to the close succession of events over time, and the associated partial overlap. Accordingly, the identification of meteorological triggers for single events (see also Section 3.4) was also impeded, since more than one trigger may have been involved. We therefore handled the classification of events very conservatively, assigning single peak or up-down/down-up events only in very clear cases, while all remaining events were ~~labeled~~ labelled clusters.

2.3.3 Linking events to meteorological conditions

For all events detected within the observation period, computed flux rates as well as prevalent meteorological conditions before, during, and after the event were collected in a database. These conditions were available as parameters in four different aggregation time steps: (1) CH_4 flux rates from both EC and wavelet processing as well as friction velocity (u_*) were used at 30 minute intervals. (2) Longwave radiation budget (I), air temperature (T), relative humidity (R) and air pressure (p) came in 10 minute time steps. (3) 1-minute CH_4 flux rates were available from the high-resolution wavelet processing. Finally (4) wind speed (U), CH_4 mixing ratios (c_{CH_4}) and wind direction (WD) were taken from 20 Hz raw data. Averages for the period during the event were aggregated between start and end times of the detected event, while for the periods before and after the event mean values were derived for 10 minute intervals before the event start or after the event end, respectively. Regarding the coarser resolution datasets (1) and (2), in each case the time step that overlapped most with the target timeframe before, during and after the event was chosen.

3 Results

3.1 Event statistics

Most statistics in this section are based on the number of minutes that were identified as part of an event. Using a flux averaging interval of $\Delta t = 1\,\mathrm{min}$, these minutes were defined as values failing the MAD test. For this analysis, the study period from ~~1st~~01 June to 15th September 2014 was split into seven blocks with a length of half a month each.

Our event detection algorithm identified 49 events for each site during the given observation period. 28 (tower 1) and 23 (tower 2) of these events were classified as clusters, while at both towers 6 events showed the typical shape of an up-down or down-up event. Including interpolation between event minutes detected by the MAD test, the cluster events covered a combined period of 65 (tower 1) and 49 hours (tower 2), with a minimum duration of 49 and 31 minutes, and a maximum duration of 410 and 329 minutes. All clusters and up-down/down-up events occurred exclusively during nighttime (21:00 - 9:00).

The remaining 15 (tower 1) and 20 (tower 2) events were characterised as single peak events. Only 4 of these occurred during daytime (9:00 - 21:00), on 12.06. and 15.06.14~~)~~, while all other events occurred at night. The duration of these peak events ranged between 2 and 43 minutes, while about half of them lasted between 9 and 21 minutes. All peak events occurred simultaneously with an event at the other tower, i.e. a corresponding counterpart event at the other tower was observed at about the same time. We will subsequently refer to simultaneous events (one from each tower) as a “pair” of events, while “event” still denotes one event from a single tower. For 13 event pairs, both events were classified as “peak events”, while the majority of the remaining peak and up-down events were paired with cluster events at the other tower.

The absolute number of detected event-minutes differed strongly between the two towers. At tower 1, their cumulative duration exceeded that observed at tower 2 by a factor of 1.4 (first half of September) to 2.8 (first half of August). As one example, in the first half of August 462 minutes were identified by the MAD test as being part of an event at tower 1, surpassing just 165 event-minutes detected at tower 2 by a wide margin. Summed up for the period ~~1st~~01 June to 15th September, a total of 1078 event-minutes were detected for tower 1, more than doubling the cumulative sum at tower 2 (539 minutes). An explanation for this difference can be found in the statistical characteristics of the ~~two datasets:~~ wavelet flux for both towers: at tower 1 7.7 % of all data were out of the range from $Q_1 - 1.5(Q_3 - Q_1)$ to $Q_3 + 1.5(Q_3 - Q_1)$, where Q_1 denotes the 25%- quantile and Q_3 the 75%- quantile. At tower 2 5.4 % of the data are out of this range, i.e., tower 2 had 2.3 % more extreme outliers (values that exceeded the interquartile range by a factor of 1.5) compared to tower 1. As the median absolute deviation is resilient regarding outliers, the MAD test ~~serves as a robust estimator that is only marginally influenced by these outliers~~ is a robust outlier classifier even if one dataset contains more outliers than another one (Hoaglin et al., 2000).

3.2 Event seasonality

For both towers, the relative distribution of events over the summer season showed similar patterns: the largest proportion of all events was detected in the first half of August (37.9 % and 30.6 % at towers 1 and 2). Earlier in the growing season, we observed a gradual increase in event occurrence from only a few percent in the first half of June to 19.3 % (tower 1) and 16.5 %

(tower 2) in the second half of July. Following the maximum in early August, the appearance of events decreased rapidly to a range between 5.9 % and 15.4 % per half month in late August – September.

Seasonal courses in event frequency appear to be linked to trends in soil thermal conditions, as indicated by e.g. the simultaneous drop in both event-minutes and mean soil temperatures in late August. At the control site, the median half monthly soil temperature at $-8\,\mathrm{cm}$ depth gradually increases from 3.6 °C in the second half of June to its maximum at 5.1 °C in the first half of August, followed by the afore-mentioned steep drop to 3.3 °C in the second half of August (details e.g. in Kittler et al., 2016). Both the general shape of the seasonal course as well as the timing of the peak agrees with the detected seasonality in event flux percentages.

3.3 Links between events and meteorological conditions

The observation The observation from section 3.1 that peak events were exclusively detected simultaneously with an event at the other tower suggests that events are typically not triggered by local changes in soil effluxes, but rather by mesoscale meteorological effects. The found correlation between event frequency and soil thermal conditions does not contradict that: a higher CH_4 emission rate from soil in times where the ground layers are (partly) decoupled from the EC level will result in a bigger amount of pooled CH_4 in a certain time – and consequently also cause a bigger flux when flushed up to the EC system.

3.3 Links between events and meteorological conditions

Due to their precise temporal delimitation, the class of peak events allowed a clear characterisation of conditions for the periods before, during and after events. Accordingly, based on the study of peak events we were able to correlate event occurrence with short-term shifts in meteorological conditions that may be responsible for triggering the observed peak events. The following paragraphs list statistics on the most relevant potential influence factors.

The air temperature (T) measured at the top of the towers showed a monotonically decreasing trend monotonically decreased in at least 60 % of all peak events (21 of 35). This temperature drift usually started more than 10 minutes before the event, and persisted until at least 10 minutes after the event. Temperature change in time in this context ranged between $-0.04\ \mathrm{Kmin^{-1}}$ within an 18 minute interval and $-0.27\ \mathrm{Kmin^{-1}}$ within a 22 minute interval. The opposite case of increasing air temperatures during a peak event was detected only once. For the relative humidity (R) at the top of the tower, in at least 29 % (10 of 35) of all peak event cases a monotonic increase was observed within the timespan of at least 10 minutes before and after the event. Increase rates for this subset of events are within the range $+0.67\ \%\mathrm{min^{-1}}$ within 9 min to $+0.86\ \%\mathrm{min^{-1}}$ within 22 min. To give an example, during the peak event that started on July 13 July at 10:39pm, and had a total length of 22 min, the temperature dropped by 5.9 K in total, while the relative humidity increased by 19 %. No case was observed where the relative humidity decreased significantly during an event.

The wind speed (U) increased in 83 % of all cases (29 of 35) during a peak event, in comparison to the last 10 minutes before the occurrence. In 48 % (14 of 29) of these situations, however, U decreased again right after the event. The largest increase in wind speed was found to be 7.4 $\mathrm{ms^{-1}}$, while for the majority of cases the difference between the time before and during the event ranged from 0.2 to 2.1 $\mathrm{ms^{-1}}$. The vertical wind speed (w), which is a direct part of all flux calculation methods, remained very close to the ideal value of zero in all these cases. Still, minor variations within a very narrow range of absolute values showed a very similar pattern, i.e. in 74 % (26 of 35) of the peak events a temporary increase was observed, followed by a decrease in 54 % of these cases (14 of 26). The friction velocity (u_*) increased at the beginning of 94 % (33 of 35) of all peak events, and decreased again right afterwards in 76 % (25 of 33) of these cases. For half of these events, only a moderate increase in the friction velocity was observed (< 0.1 to 0.3 $\mathrm{ms^{-1}}$), while the full range of shifts lay between < 0.01 and 0.7 $\mathrm{ms^{-1}}$.

For the stability of atmospheric stratification (zL^{-1}, with z as measurement height and L as Obukhov length), no general pattern for the conditions before, during and after a peak event could be found. In 43 % of all events (15/35) there was no change in stability over time while the event occurred. For 7 cases, the stability during the 30 minute interval where the event occurred shifted towards more unstable stratification, while for 8 cases a change in the opposite direction was observed. About 23 % (8 of 35) of all events occurred during unstable stratification ($zL^{-1} < -0.0625$), exceeding the average data fraction of unstable stratification during night time (13 % for tower 1, 18.5 % for tower 2). Due to the site being located in the high Arctic latitudes, (slightly) unstable stratification was also likely to occur at night as long as the shortwave downwelling radiation $K\downarrow > 20\,\mathrm{Wm^{-2}}$. The stability before, during and after daytime events was always neutral ($-0.0625 \leq zL^{-1} \leq 0.0625$).

Summarising, since the majority of events were detected during the night (21:00 - 9:00), it could be expected that a large number of cases would be subject to systematically falling temperatures, and associated increases in relative humidity. On the other hand, the high percentage of peak events that are characterised by an increase and subsequent decrease in wind speed and friction velocity indicates that turbulence intensity in the atmospheric surface layer is a major influence factor. With a higher-than-average fraction of cases with neutral atmospheric stability associated with peak events, it can be speculated that such stratification conditions promote the impact of sporadic increases in mechanically generated turbulence that lead to the high CH_4 emissions.

3.4 Case study: Nighttime advection

To demonstrate the characteristics of a typical peak event, as well as the approach we used herein to analyse and interpret it, the following sub-sections provide a detailed description of a case study during the night from ~~August 2-3,~~ 02 to 03 August 2014. That event was already described by Schaller et al. (2017b) to show that wavelet analysis is able to resolve that event. Schaller et al. (2017b) discussed the calculation method, comparing each the Mexican hat and the Morlet mother wavelet and showed that the Mexican hat was able to resolve the event precisely in time. Based on that findings, we show the meteorological conditions and analyse them to identify the underlying triggering mechanism. We chose this particular event because conditions are well documented through photographs taken by the observer, which strongly support our theory about the underlying triggering mechanism as described later in this section.

3.4.1 Meteorological conditions during event period

Within the given night, at both tower 1 (Fig. 2) and tower 2 (similar general patterns, data not shown) no signs of an upcoming event could be registered until 11:30pm. Starting at 11:00pm, a light breeze from the southeast with a maximum wind speed around 1.5 ms^{-1} gradually decreased to a calm. The mean CH_4 concentration in this half hour was 2102 and 2112 pbb at towers 1 and 2, and the friction velocity as a proxy measure for aerodynamically generated turbulent motion was very low (< 0.1 ms^{-1}). At 11:31pm, both towers registered an increase in CH_4 concentrations, associated with a minor increase of the wind speed. A temporary shift in wind direction to the northwest was reversed back to the southeast after a few minutes.

Around 11:45pm, the wind speed continued increasing to about 1.5 ms^{-1}, and a few minutes later the wind direction turned to the east/northeast. The onset of the event itself was detected at 11:55pm (tower 1, Fig. 3) and 11:59pm (tower 2, Fig. 4), and this period of high fluxes lasted until 0:~~18am~~ 18 (tower 1) and 0:~~07am~~ 07 (tower 2). During the time interval 23:30 to 23:59 when the event started, the half hourly averaged friction velocity u_* increased substantially, disrupting the previously existing decoupling of surface and higher atmosphere due to stable stratification. This increased turbulence intensity potentially vented CH_4 pools that had accumulated near the ground towards the EC systems at tower top. Shortly after the end of the event, the wind direction at both towers changed from the east back to the southeast, i.e. the same direction as before the event. The CH_4 concentrations also decreased. Wind speeds, on the other hand, did not decrease, while the friction velocity decreased marginally.

3.4.2 Wavelet fluxes during event period

The mean Mexican hat CH_4 flux rate during the event was calculated as $181\,\mathrm{nmol\,m^{-2}\,s^{-1}}$ at tower 1 (tower 2: ~~392~~$392\,\mathrm{nmol\,m^{-2}\,s^{-1}}$). This value is substantially higher than the $7\,\mathrm{nmol\,m^{-2}\,s^{-1}}$ observed in the 20 minute period before the event (tower 2: ~~26~~$26\,\mathrm{nmol\,m^{-2}\,s^{-1}}$) as well as the $19\,\mathrm{nmol\,m^{-2}\,s^{-1}}$ in the 20 minute period after the event (tower 2: ~~88~~$88\,\mathrm{nmol\,m^{-2}\,s^{-1}}$). The relatively high mean flux rate after the event at tower 2 is caused by a short period of higher fluxes up to 0:~~20am.~~ 20. In addition to the average flux rates, the standard deviation of fluxes at tower 1 ($118\,\mathrm{nmol\,m^{-2}\,s^{-1}}$) also significantly exceeded the values before ($53\,\mathrm{nmol\,m^{-2}\,s^{-1}}$) and after ($31\,\mathrm{nmol\,m^{-2}\,s^{-1}}$) the event (tower 2 showed similar overall behaviour).

The exact times when the flux peaks occurred coincided with the highest energy and most positive contribution to the wavelet flux, as indicated in the wavelet cross-scalograms of both towers (Figs. 3, 4). Sensitivity studies revealed that the choice of the upper wavelet scale integration limit J (Eq. (13) in Schaller et al., 2017b) and thus the maximum wavelet period λ_{max} significantly impacts the flux computation: an extension of the upper period integration limit to $\lambda_{max} = 184\,\mathrm{min}$ ~~(Mexican hat) as well as $\lambda_{max} = 190\,\mathrm{min}$ (Morlet)~~ showed a significant increase of ~~both wavelet fluxes~~the wavelet flux. Still, we did not find any indication that hinted at an influence of gravity waves during this particular case study. The ~~use of the Morlet wavelet (Fig. 5, top) resulted in a widely expanded area of high flux contribution over the whole study time from 23:00 to 1:00, where the low frequency periods from 40 to 180 min contributed most to the total flux. In addition, the detailed cross-scalogram up to a period of 30 min (Fig. 3, 4) demonstrated that the lowest period of substantial contribution was around 10 min. In contrast to the reduced resolution of the Morlet wavelet in time domain, the~~ Mexican hat cross-scalogram (Fig. 5~~, bottom~~) generated a sharp temporal transition between periods of high and low flux contributions, and this separation allowed us to precisely constrain the duration of the event~~. The latter finding verified that the observed contribution in the Morlet cross-scalogram indeed originated from the event itself, and was not carried over from adjacent periods.~~ , where the low frequency periods from 40 to 180 min contributed most to the total flux.

For ~~all three~~ both flux processing approaches compared herein, average CH_4 flux rates for the 30-minute interval that contained the peak event are summarised in Table 1~~for both towers~~. These results indicate that for the chosen event period, ~~both wavelet methods~~ the Mexican hat wavelet yielded systematically lower fluxes compared to the EC reference. ~~In contrast to a previous study that focused on conditions of well-developed turbulence with high quality data eddy-covariance data (Schaller et al., 2017b), in this case deviations from EC fluxes based on the Morlet wavelet ($EC - WV_M$ tower 1: 87 ; tower 2: 66) were larger than those found for the Mexican Hat ($EC - WV_{Mh}$: 52; 34).~~

~~Differences in the performance of both wavelet approaches can be explained by the different characteristics of the wavelets: as shown in Fig. 5, the better resolution in the time domain of the Mexican hat wavelet led to higher absolute flux rates that were constricted to a narrower time window compared to the Morlet wavelet. This phenomenon can also be observed in the cross-scalogram up to $\lambda = 30$ min (Figs. 3, 4), where Morlet results showed the same flux over a wider timespan than those for the Mexican hat. Despite the limitation of the maximum period to $\lambda = 33$ min, the Mexican hat may nonetheless resolve flux contributions above that limit, because its resolution in frequency domain is worse compared to the Morlet wavelet. Therefore, as demonstrated by Schaller et al. (2017b), for longer-term flux integration the fluxes based on the Morlet wavelet should provide the most accurate results, while for this specific 30-minute time window the Mexican hat results should be most trustworthy. Differences from the eddy-covariance fluxes strongly~~ This differences from the EC fluxes suggest that regular ~~eddy-covariance~~ EC data processing yielded biased results ~~(i.e a systematic overestimation of fluxes)~~ caused by non-stationary conditions, if these EC periods were not filtered out and gap filled.

3.4.3 Cold-air advection from mountains

Around ~~11:45pm~~23:45, the first signs of a developing ground fog were observed and also documented by photographs. Additional pictures were taken during the following minutes near tower 2 (Fig. 6, top), i.e. around the time the events began. All pictures demonstrate a ground fog moving in from the northeast, where the ridges of two nearby hills, Mount Rodynka (351 m above sea level) and Mount Panteleicha (632 m a.s.l., Fig. 7), are located. The time at which this fog reached tower 1 coincided well with the onset of the events. Shortly after midnight, another photograph (0:~~11am~~11) demonstrates that the fog had largely disappeared, well aligned with the sharp decrease in flux magnitude that indicates the end of the event.

The observed ground fog was also reflected in the meteorological data (Fig. 2). During the slow buildup of the ground fog in the period between ~~11~~23:20 and ~~11:50pm~~23:50, the temperature at 2 m above the ground decreased by 1.3 K, while the relative humidity showed a small increase in the same timespan. Within the same period, the longwave net radiation, which is a good measure of the temperature difference between the sky and the ground, decreased to minimum values of 23 $\mathrm{Wm^{-2}}$, which implies a low temperature difference between the surface and the clouds, indicating very low clouds or fog.

3.5 Event triggers

Our statistics on meteorological conditions before, during and after the detected peak events reveal a common pattern for all event situations, regardless of the mechanism that actually triggered the event: during a period of weak turbulence, the surface was at least partially decoupled from the lower atmosphere where the flux sensors were positioned. CH_4 that was emitted from the soil during this period could not properly be mixed up to the sensor level, therefore likely forming a CH_4-rich layer of air near the ground. In all event cases, either a general change in atmospheric conditions or a short-term meteorological phenomenon broke up the decoupling between the layers. As a consequence, the CH_4 pool in near-surface air layers was vented up to the eddy-covariance EC level, and therefore detected as a pronounced peak in the flux rate.

This sequence of conditions strongly suggests that atmospheric mixing, and not CH_4 emissions processes from the soil, is the dominating mechanism behind the flux peak events as detected by our algorithm. Since we did not observe a single case study where a strong flux peak was detected within a previously well-mixed situation, our findings indicate that ebullition events, which can e.g. be detected at smaller scales with soil chambers (e.g. Kwon et al., 2017), usually are too small as individual emissions, or not coordinated enough spatially across the relatively large footprint area (approx. $4000\,\mathrm{m}^2$ at neutral stratification) to be detected by an eddy-covariance systemthis EC setup with a sensor height $\geq 4.9\,\mathrm{m}$ above ground. Following the detailed description of the case study presented in the preceding section, in the subsections below we briefly discuss several typical meteorological situations that were also observed to trigger events. Although there were no additional boundary layer or gradient measurements available, all identified mesoscale phenomena in the following subsections were always clearly visible at both towers, which supports the findings.

3.5.1 Cold air drainage

At the Chersky floodplain sites, about 50 % of all events occurred with wind directions from the E/NE, while only 3 % of all events fell into the S/SE (Table 2). These observations are in stark contrast to the local wind climatology, which lists just 16.2 % of cases in the E/NE sector, while the S/SE sector dominates with 37.9 % (values based on observations from tower 1, averaged for whole observation period). An explanation for this discrepancy can be found in the mesoscale wind field at this particular location, which may be prone to katabatic winds from the E/NE sector at night: typically, nighttime events from these sectors are characterised by decreases in the longwave net radiation I to values around or below 20 Wm^{-2} exactly during or a short time after the event. This observation indicates that temperature differences between above and below the net pyrgeometer rapidly decreased, which could be a sign for low-level fog layers moving through.

3.5.2 Weather fronts

Weather fronts are typically associated with substantial shifts in e.g. air temperature, wind speed or wind direction. As an example, we observed such signs of a weather front passing the site on June 12 , June 2014, where the previously falling air pressure started increasing rapidly by 1 hPa per hour, combined with a wind speed increase from about 5 to 10 ms^{-1}. With the stability of atmospheric stratification being neutral during this daytime event, it is unlikely that the mechanical turbulence associated with the frontal passage ejected CH_4 pools that had previously been accumulated close to the ground. Instead, it can be speculated that pressure fluctuations associated with the stronger turbulence washed out CH_4 from micropores within the top soil layers. However, particularly at night an accumulated CH_4 pool close to the surface should be the most likely source for a peak event, as e.g. observed during the night of June 13 , June 2014. Here the wind speed increased rapidly from about 1 to 4 ms^{-1}, breaking up decoupled air layers between the surface and sensor level, and in the process venting the CH_4 that had previously been accumulated over time. This event was registered as rapidly shifting CH_4 mixing ratios at the tower top, which decreased within 10 min, while the wind speed continuously remained high.

3.5.3 Atmospheric gravity waves

For one pair of events occurring on ~~July~~ 12 ~~,~~ July 2014, conditions at both towers indicated low atmospheric turbulence intensity ($u_* < 0.3\,\mathrm{ms}^{-1}$), associated with a vertical temperature inversion and very low horizontal wind speeds. These conditions were interrupted at 3:~~10am~~10, when the wind speeds first rapidly increased to 2.5 ms^{-1}, only to drop to the previous low level (0.5 ms^{-1}) immediately afterwards. This step change was followed by both CH_4 concentration and vertical wind speed, where the former showed a sharp increase within seconds from around 2500 up to 5067 ppb (tower 1). For this situation, the Morlet crosswavelet spectrum showed a period around 5 to 10 minutes that contributed most to the observed flux. This information, together with the characteristics of the high frequency data, are indications that this particular event may have been triggered by an atmospheric gravity wave reaching the ground (Nappo, 2013; Serafimovich et al., 2017); however, lacking soundings of the vertical structure of the atmospheric boundary layer, this assumption remains speculative.

3.5.4 Low level jets

Low level jets appeared to be the triggering mechanism for two pairs of events with distinctive characteristics. In one example, on ~~July~~ 31 ~~,~~ July 2014, very low wind speeds (0.5 ms^{-1}) from NW to N resulted in a stably stratified lower atmosphere and a strong temperature inversion. In the period before the event occurred, the long-wave net-radiation decreased from about 30 Wm^{-2} to $< 15\ \mathrm{Wm}^{-2}$, which could indicate that low stratus clouds were moving in. The onset of the event itself was marked by a rapid increase of the wind speed and a shift in wind direction by at least 45° to S to SW, which led to a sharp rise in CH_4 concentration with maximum values around 4120 ppb (tower 1). The flux rate also substantially increased for 5 minutes. Within the next half hour, the wind speed gradually decreased, then the wind switched back to the direction before the event. Under nocturnal stable stratification with a typically shallow stable boundary layer, the observed sudden increase in wind speed in combination with a change in wind direction are indicators for a significant vertical wind shear associated with a low level jet, which was found to be connected with a significant increase in gas fluxes (Karipot et al., 2008; Foken et al., 2012c). But, as already mentioned for gravity waves, additional boundary layer measurements would be necessary to validate this assumption.

3.5.5 Onset of turbulent flow

The three remaining event pairs were detected under stable or neutral conditions, and characterised by a gradually increasing, non-fluctuating wind speed, but no change in flux rates just before the event occurred. One example from ~~July~~ 11 July demonstrated that only when the increase in winds finally started to yield fluctuations in wind speed, the event occurred and the CH_4 concentration increased by about 500 ppb within 15 min. After the event peak was reached, the concentration decreased quickly, while the wind speed fluctuations did not change. These patterns indicate that, before the event, vertical decoupling of the shallow boundary layer resulted in a laminar wind flow at sensor height, which explains the dampened fluctuations in wind speed. With the shift from laminar to turbulent flow, the previously accumulated CH_4 near the ground could be transported up the sensor height, resulting in the observed flux peak. This observed change from laminar to turbulent flow is very similar to the conditions associated with a low level jet, but due to the missing shift in wind directions we decided to separate both triggering mechanisms herein.

4 Discussion

4.1 Advective contributions to flux events

The ~~eddy-covariance~~ EC method is based on the assumption that observations of turbulent fluctuations at a single point in space within the atmospheric surface layer can be used to obtain a representative flux rate from the ecosystem surrounding the flux tower. It is therefore of crucial importance for the interpretation of the impact of events for calculation of the local flux budgets whether the emitted CH_4 was produced locally and just temporarily pooled near the surface, or horizontally advected towards the measurement location. Advective transport would bias the local mass balance of CH_4 and any other atmospheric constituent to be monitored, therefore seriously undermining the theoretic assumptions that the ~~eddy-covariance~~ EC technique relies on (Aubinet, 2008). If the fluxes detected by the instruments do not originate from the target area if advection is present, they should not be considered in the local flux budget. Accordingly, the detection of advection as a triggering mechanism behind an event deserves special attention, since inclusion of such data into the flux budget would lead to a systematic overestimation of fluxes from the local ecosystem.

To differentiate between events with and without advective flux contributions, the extension of the wavelet integration period provides essential information. For all methods compared herein, peak events are characterised by an intensive high-frequency turbulent component within an integration interval of up to 30 minutes, which explains the increase of the flux. In addition to this, events that were influenced by advection also showed significant flux contributions from longer integration periods. This finding indicates that the elevated flux rates were not exclusively driven by turbulence and the venting of local CH_4 pools near the ground, but also contained contributions from mesoscale motions spanning periods of minutes to hours.

The correlation in temporal trends of turbulence intensity and CH_4 mixing ratios after the event can also be taken as an indicator for the source of the CH_4. If the excess CH_4 that created a peak flux during a detected event was coming from a limited source, i.e. local emissions that had been pooled in air layers close to the ground, the increased CH_4 concentrations usually dropped to lower levels after only a few minutes. In this case, elevated flux rates also lasted for only a few minutes, while the increased turbulent mixing that initiated an event often persisted for a long time thereafter. In contrast, if the triggering mechanism had been advective transport, both CH_4 concentrations and turbulence intensity should remain high for an extended period of time. Here, the reservoir that feeds the peak CH_4 fluxes is substantially larger, since it is originating from a different region and is transported to the tower by katabatic winds. However, the differentiation is not as clean as that based on the wavelet integration periods, since the maximum amount of CH_4 that can be vented from a local source close to the surface in the absence of advective contributions depends on many factors. Most importantly, the time since decoupling and the time since the last event took place influences how much CH_4 can have re-accumulated, but the current CH_4 emission rate from the ground and the intensity of the vertical mixing with the onset of the event also play a role in how long it will take until a local source will be depleted. To summarise, based on the length of an event alone a clean distinction between events with and without advective flux contributions cannot be performed~~, but for events with a duration of 15 minutes or more, advection is likely to be present~~.

4.1.1 Implications for designing an optimum observation strategy

Statistics for the Chersky site show that, on average for the observation period in summer 2014, an event occurred about every other day (0.46 events per day). With the longer cluster events lasting for up to several hours, the average time covered by an event per day is 36.4 minutes at tower 1, and 27.5 minutes at tower 2. Assuming that such events, at best, lead to lower quality rating of the ~~eddy-covariance~~ EC fluxes, and in the worst case constitute systematic biases to flux budgets determined through the ~~eddy-covariance~~ EC technique, their net impact on longer-term flux budgets may be substantial, which should be investigated in a subsequent study. Our results demonstrate two major pathways through which events can systematically disturb the flux budget determined through the conventional ~~eddy-covariance~~ EC approach:

In the absence of advection, an event such as e.g. a peak event that produces a short but intense outburst of CH_4 with a duration of (significantly) less than the common integration interval for ~~eddy-covariance~~ EC (30 minutes) constitutes a substantial violation of the steady-state assumption. As a consequence, the Reynolds decomposition that separates the high-frequency signal into a mean and turbulent component may produce incorrect positive and negative fluctuations of both vertical wind and trace gas concentrations. Depending on the nature of the event, the observation may in part be discarded as a spike, or the entire 30-minute interval may be flagged as very low quality data and in turn be sorted out during data analysis, to be replaced by gap-filled values. In both cases, provided that the event was not caused by advection, the high emission event would disappear from the long-term CH_4 flux budget, effectively leading to a systematic underestimation of net emissions. As a second potential scenario, the incorrect Reynolds decomposition may lead to both positive and negative flux biases, again dependent on the nature of the event, while a medium quality flag will lead to the inclusion of this flux into long-term budget computation. In summary, the presence of events will introduce additional uncertainty into long-term flux observations, and in the case of CH_4 is likely to lead to a systematic underestimation of flux budgets since peak events are likely to be sorted out by the processing software.

As a second major pathway to disturb ~~eddy-covariance~~ EC flux budgets, events hold the potential to bias the local mass balance through advective flux contributions. Our statistics demonstrate that cold air drainage is the responsible trigger for about half of the peak events detected by our algorithm at the Chersky observation site. Wind statistics and regional topography structure support the assumption that these events are associated with horizontal advection of CH_4 that contributes a significant portion of the excess flux. Based on overall event statistics, this means that the site experiences on average about 2-3 events per month with potential advective flux contributions during the growing season. For several reasons, the potential bias of this effect on the ~~eddy-covariance~~ EC flux budget cannot be quantified yet. First, the total flux during an event triggered by cold air drainage will be a composition of local CH_4 emissions pooled near the surface and advected CH_4. Second, a portion of the affected events will be sorted out by the eddy-covariance EC quality flagging procedure, and (in this case rightfully) removed from the long-term budget computation. Therefore, as for the violation of steady-state conditions, advective events need to be considered as a potential cause for systematic biases, in this case overestimation, of eddy-covariance EC flux budgets.

To facilitate a differentiation between these pathways, it would be important to validate these mesoscale triggering mechanisms in future field experiments. Influences by low level jets or gravity waves could be verified by additional measurements of the atmospheric boundary layer, e.g. using a well established technique like SODAR/RASS (SOnic Detection And Ranging / Radio Acoustic Sounding System). The conceptual model of katabatic winds from the hill ridge located north / north-east of the study site could be investigated by installing additional nocturnal temperature measurements at heights of 20 to 50 cm in the hills and optionally also between the site and the hills. In order to visualise the events and to achieve a better understanding of how the accumulated CH_4 is mixed up to the sensor during an event, it could be helpful to use the high-resolution fibre-optic temperature sensing approach, which was newly developed by Thomas et al. (2012) and has already been established for studies on cold air layers in the nocturnal stable boundary layer (Zeeman et al., 2015). Additional vertical and horizontal CH_4 concentration profiles could also be useful to visualise the flushing process of previously stored CH_4 below the EC measuring level.

4.1.2 Role of cluster events

The potential role of events classified as ”clusters“ (coherent pattern, but no uniform shape) on potential systematic biases in flux budgets was excluded from this study. Clustered events, which made up the vast majority of event minutes detected by our algorithm, hold the potential to yield very different results between eddy-covariance EC and wavelet methods; however, a uniform classification of e.g. environmental conditions and flux patterns was not possible here, therefore conducted here, because this study focused on events that occur at short timescales, i.e., last only for minutes or some tens of minutes. Therefore a detailed investigation needs to be postponed to a follow-up study field study including additional boundary layer measurements that will be exclusively dedicated to this phenomenon. It is very likely that these clusters were a result of recurring events, and complex recirculation of air masses enriched in trace gases.

5 Conclusions

We showed that wavelet analysis can serve as a suitable method to resolve events in the order of minutes, which typically occurred at night and were not caused by ebullition or other local processes in the soil, but by different mesoscale meteorological phenomena. EC The signs of those phenomena were always visible at both towers (distance: 600 m) simultaneously. The EC method failed to resolve the events correctly, because the steady-state assumption was not fulfilled, but it can be assumeed that during regular EC processing these times usually would be filtered out and gap filled.

In detail, this study demonstrates that events, which represent a violation of the basic assumption for the application of the eddy-covariance EC technique, are a regularly occurring phenomenon at the observation site Chersky in Northeastern Siberia. The exact localisation of these events in time as well as their duration and magnitude was made possible using wavelet analysis.

All events evaluated in this study started with a similar general setting: CH_4, as emitted from the soil, accumulated near the ground because the surface layer was decoupled from the overlaying air during time periods of low turbulence. The breakup of these conditions was triggered by different mechanisms on the mesoscale. These mechanisms included the passage of fronts, atmospheric gravity waves, low level jets, and katabatic winds. All events were characterised by sudden peaks in CH_4 mixing ratios, often connected with increased horizontal wind speeds. This led to turbulent mixing and thus to short-term events with increased CH_4 fluxes. ~~We can rule out in virtually all cases~~ It is very unlikely that the observed peaks were the result of sudden, simultaneous CH_4 releases from the soil.

We found a strong positive correlation of short-term extreme CH_4 flux events during the season with high soil temperatures and high median CH_4 rates. This conjunction was likely formed by an increased CH_4 production during times of high soil temperatures, which facilitated the accumulation of substantial CH_4 pools when the surface layer was decoupled from the air above. Further, we found that events that were triggered by katabatic winds ~~,~~ advected further CH_4 to the site, which must have been emitted at a remote place within the flow path of the advection. As half of all events within our dataset were linked to advection, the peaks therefore do not necessarily represent the characteristics of the local CH_4 production. This leads us to conclude that the respective flux events do not necessarily reflect the conditions at the site or within the EC flux footprint.

The portability of these results to other flux observation sites, within the Arctic and beyond, depends largely on prevalent local and regional atmospheric transport and mixing conditions. Particularly at sites where low winds at nighttime frequently enable an efficient decoupling of the surface layer, it is likely that similar phenomena may occur. ~~The~~ As this study focused on the characterisation of single non-stationary events, the net impact of such events on the long-term CH_4 budget as well as a comparison with typical EC gap filling approaches still needs to be quantified, particularly since a large fraction of events were present in the form of clusters that proved difficult to classify and analyse. Such an analysis will be subject of a follow-up study that is currently in progress.

Competing interests. The authors declare that they have no conflict of interest.

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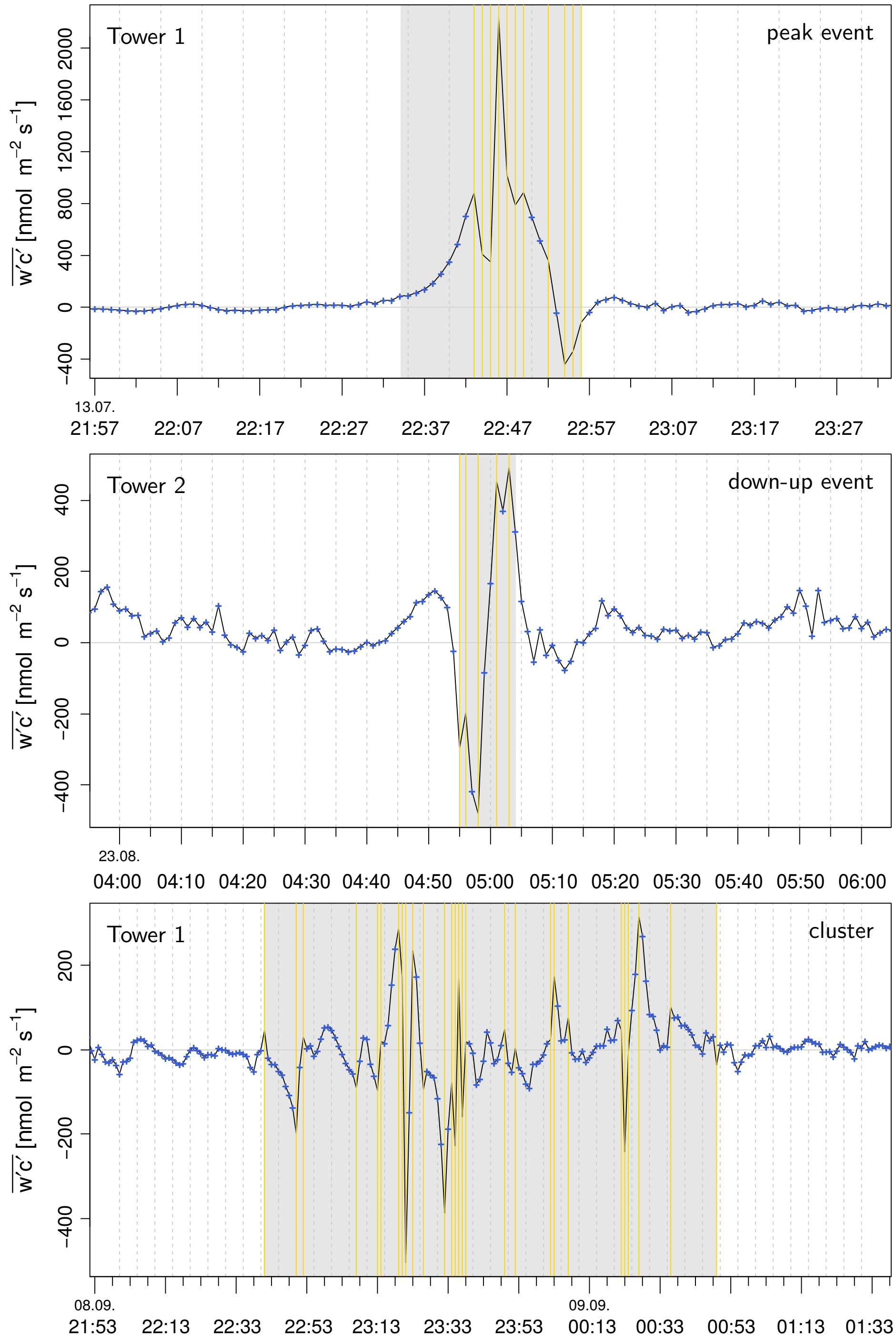

Figure 1. Examples for peak events (top), down-up events (center) and clustered events (bottom) identified using the Mexican hat wavelet flux. Data points marked with a yellow vertical line were detected as event-minute using the MAD test with threshold $q = 6$, while all other non-event data was marked with blue plus signs. The manually detected event length is shaded in grey colour.

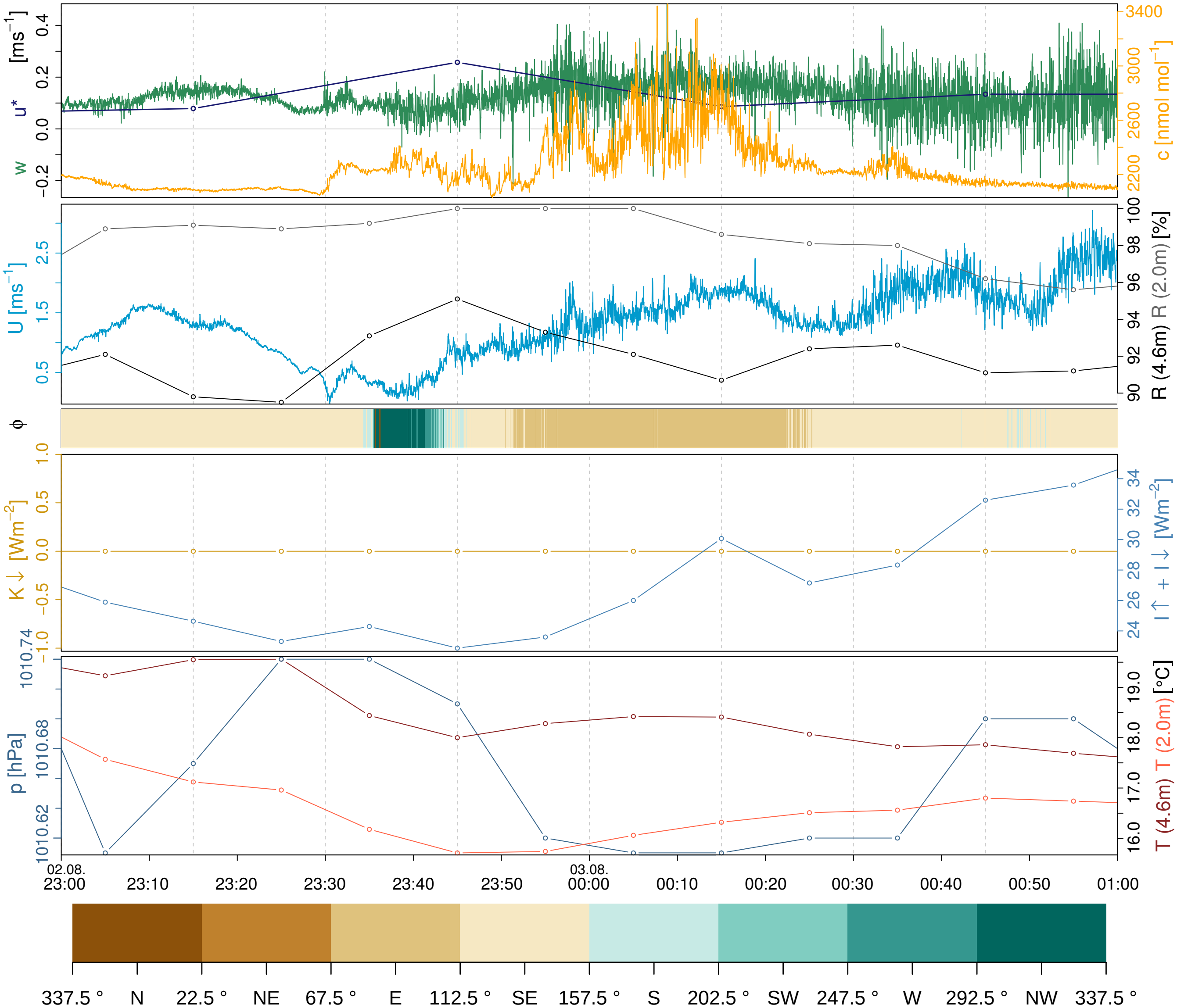

Figure 2. Meteorological conditions observed at tower 1 during the case study event of ~~August 02.~~02/~~03.,~~ 03 August 2014. Wind velocity U, vertical wind speed w and CH_4 mixing ratio c as well as wind direction ϕ are shown in a time resolution of 20 Hz. The friction velocity $u*$ was averaged to 30 min, while all other data were averaged to 10 min: relative humidity R and air temperature T (both in each 2.0 and 4.5 m above ground) as well as the longwave radiation balance $I\downarrow + I\uparrow$, the shortwave downwelling radiation $K\downarrow$ and air pressure p. The bottom panel shows a legend for ϕ.

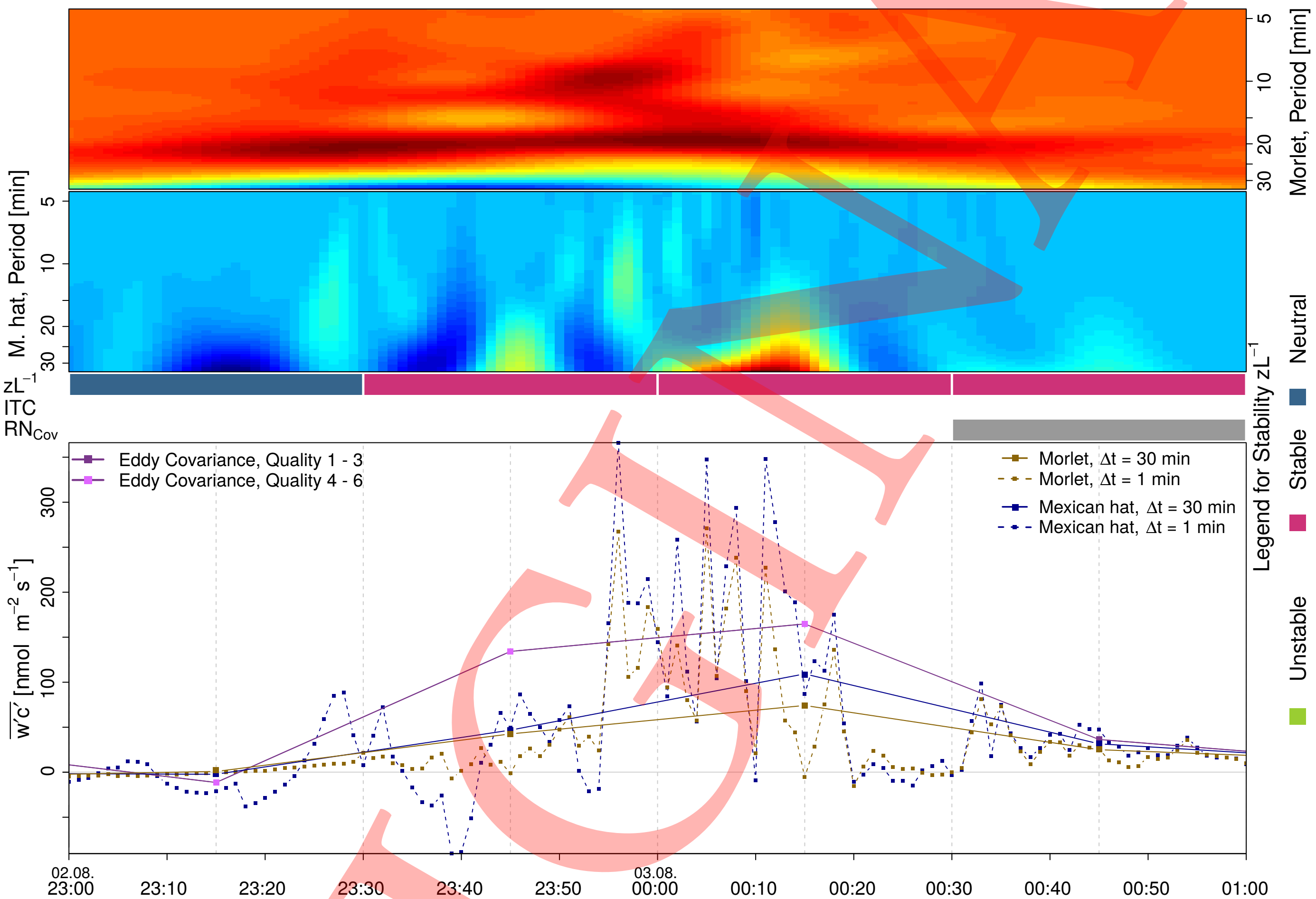

Figure 3. Wavelet cross-scalograms and flux rates computed for tower 1 during the case study event on August 02./03., 2014. The colours in the wavelet cross-scalograms between w and c denote the flux intensity, with warm colours indicating the highest flux contributions. Gray coloured intervals at ITC and RN_{Cov} refer to each best turbulent ($ITC < 30\%$) and steady-state ($RN_{Cov} < 30\%$) conditions according to Foken et al. (2004). The quality classes 1 – 9 for EC refer to the overall flux flagging system after Foken et al. (2004).

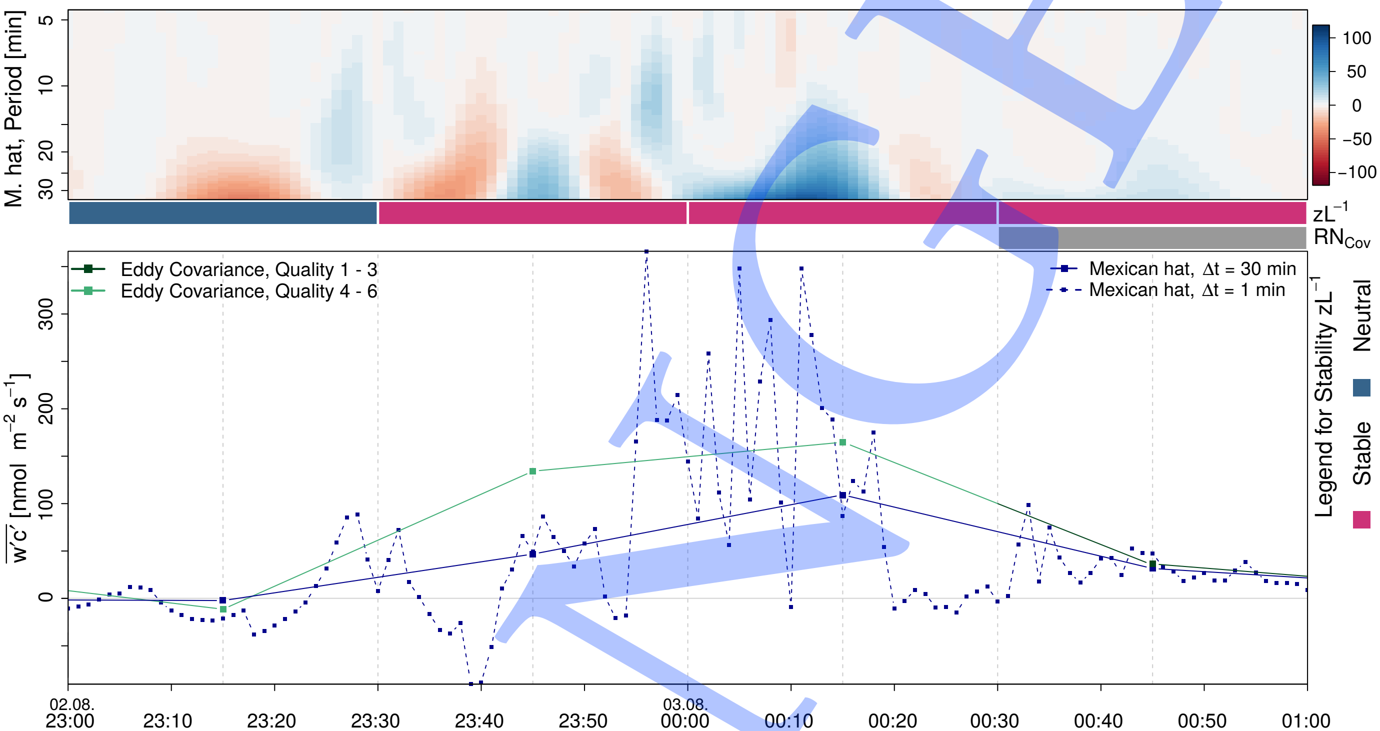

Figure 3. Wavelet ~~cross-scalograms~~ cross-scalogram and flux rates computed for tower 1 during the case study event on ~~August 02.~~02/~~03.,~~ 03 August 2014. The colours in the wavelet ~~cross-scalograms~~ cross-scalogram between w and c denote the flux intensity (wavelet coefficient), ~~with warm~~ where intensive colours ~~indicating the highest~~ indicate higher flux contributions downwards (negative, dark red) or upwards (positive, blue). The whole scalogram is outside the cone of influence (COI). Atmospheric stratification zL^{-1} (Foken et al., 2004) for every 30-min-interval was denoted as blue (neutral) or pink (stable) color bar right below the cross-scalogram. Gray coloured intervals ~~at ITC and~~ in the line labelled RN_{Cov} refer to ~~each~~ best ~~turbulent ($ITC < 30\%$) and~~ steady-state ($RN_{Cov} < 30\%$) conditions according to Foken et al. (2004). The quality classes 1 – 9 in the bottom panel for EC refer to the overall flux flagging system after Foken et al. (2004).

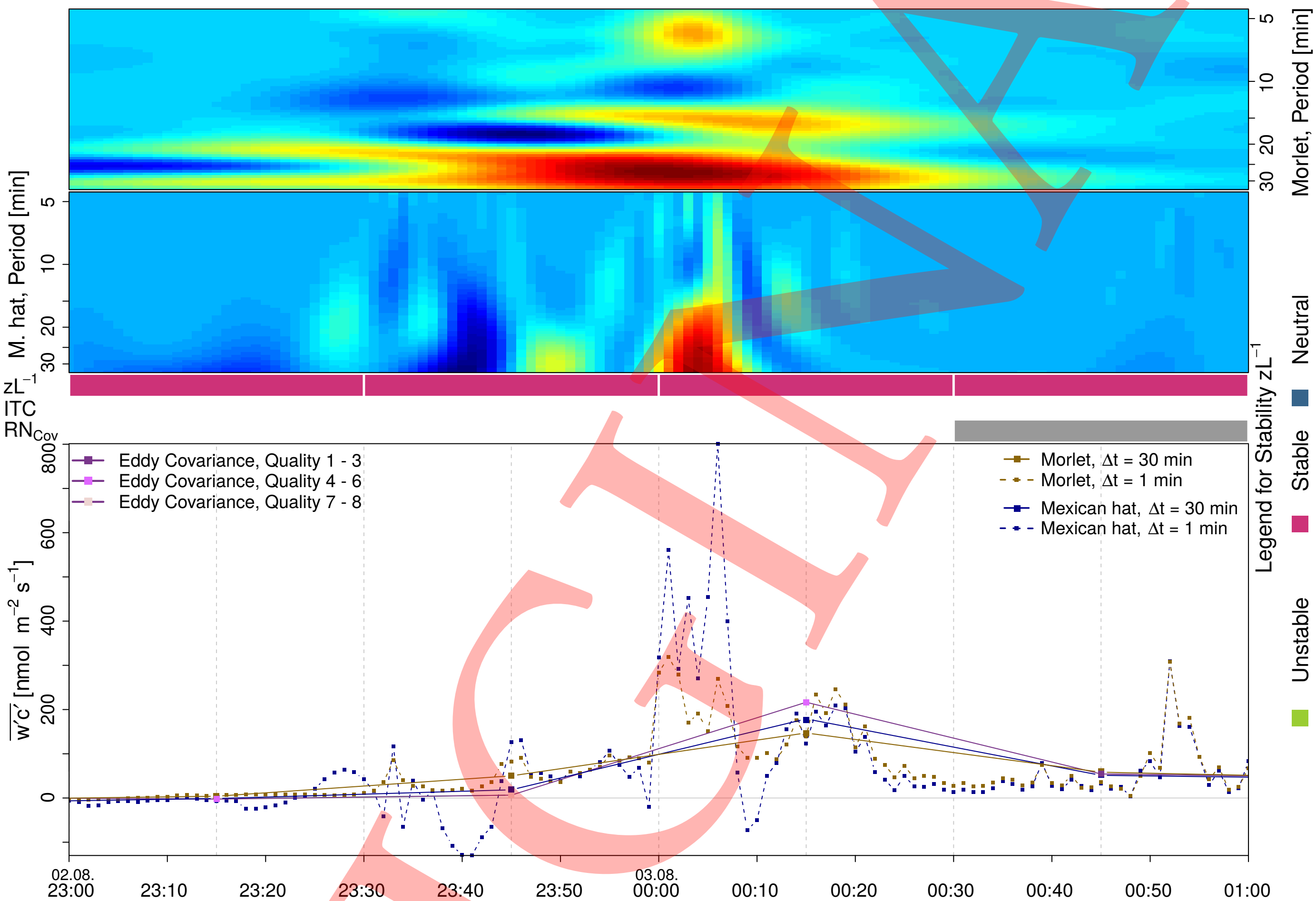

Figure 4. Wavelet cross-scalograms and flux rates computed for tower 2 during the case study event on August 02./03., 2014. The colours in the wavelet cross-scalograms between w and c denote the flux intensity, with warm colours indicating the highest flux contributions. Gray coloured intervals at ITC and RN_{Cov} refer to each best turbulent ($ITC < 30\%$) and steady-state ($RN_{Cov} < 30\%$) conditions according to Foken et al. (2004). The quality classes 1 – 9 for EC refer to the overall flux flagging system after Foken et al. (2004).

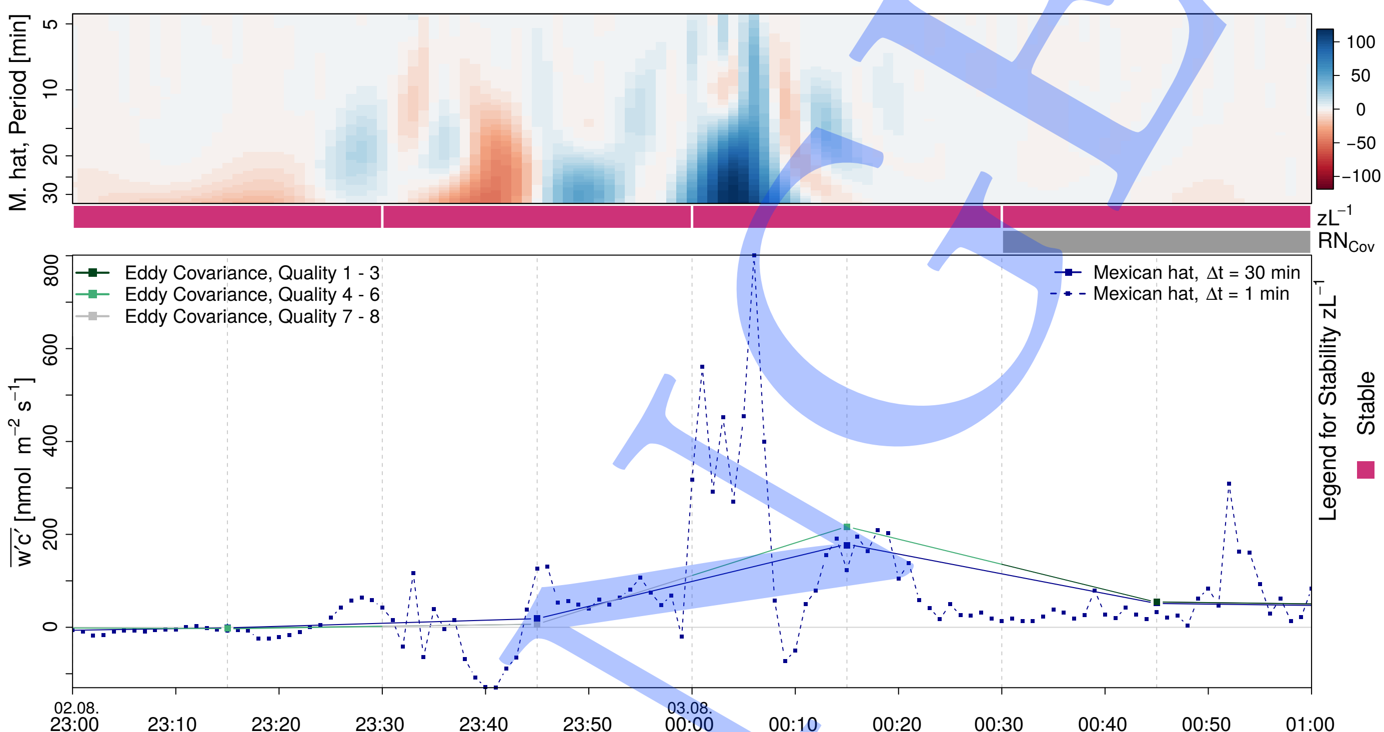

Figure 4. Wavelet ~~cross-sealograms~~ cross-scalogram and flux rates computed for tower 2 during the case study event on ~~August 02.~~02/~~03.,~~ 03 August 2014. The colours in the wavelet ~~cross-sealograms~~ cross-scalogram between w and c denote the flux intensity (wavelet coefficient), ~~with warm~~ where intensive colours ~~indicating the highest~~ indicate higher flux contributions downwards (negative, dark red) or upwards (positive, blue). The whole scalogram is outside the cone of influence (COI). Atmospheric stratification zL^{-1} (Foken et al., 2004) for every 30-min-interval was shown as coloured bars right below the cross-scalogram and stable (pink coloured) during the complete time. Gray coloured intervals ~~at ITC and~~ in the line labelled RN_{Cov} refer to ~~each~~ best ~~turbulent ($ITC < 30\%$) and~~ steady-state ($RN_{Cov} < 30\%$) conditions according to Foken et al. (2004). The quality classes 1 – 9 in the bottom panel for EC refer to the overall flux flagging system after Foken et al. (2004).

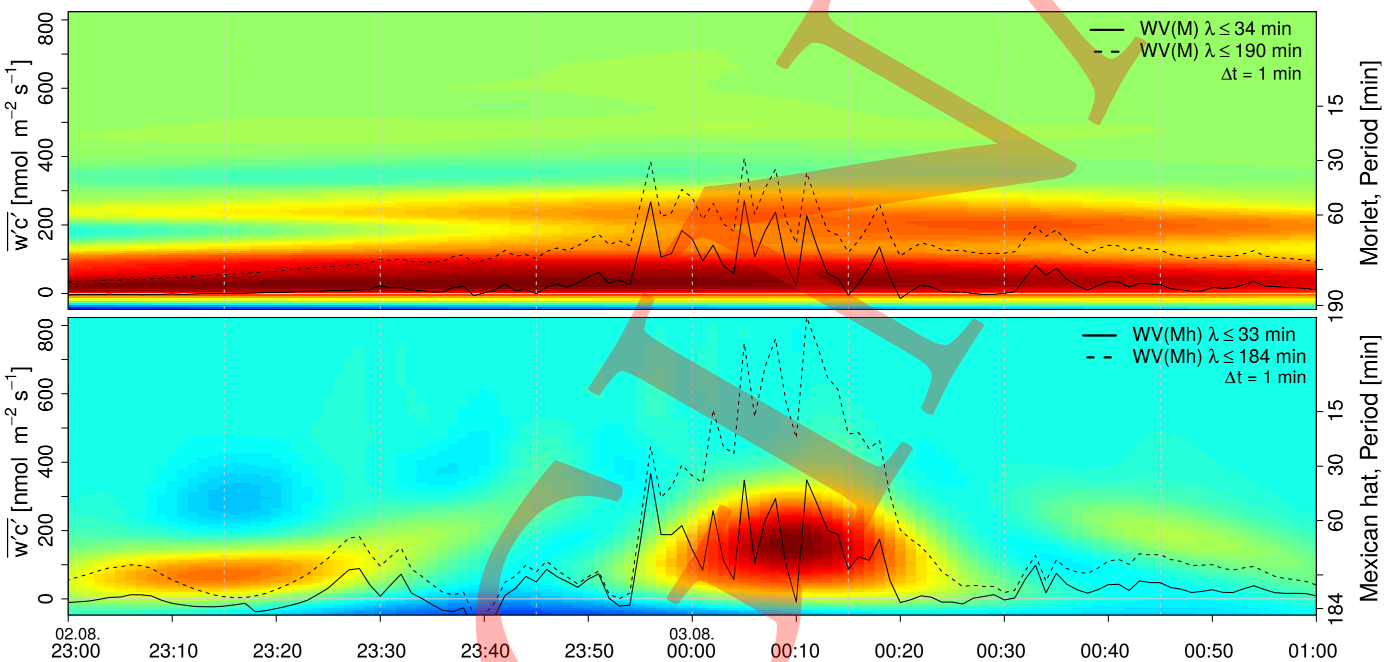

Figure 5. Wavelet cross-scalogram for the period 02.08.14, 11:00pm – 03.08.14, 1:00am at tower 1 for Morlet (top) and Mexican hat wavelets (bottom). The right axis numbers the period, while plotted lines refer to the left axis. Solid lines show the flux for an integration over all periods from $\lambda = 2 \cdot \delta t$ to $\lambda = 33\,\mathrm{min}$ (Mh / Mexican hat) and $\lambda = 34\,\mathrm{min}$ (M / Morlet), while the dashed line gives the flux up to $\lambda = 184\,\mathrm{min}$ (Mexican hat) and $\lambda = 190\,\mathrm{min}$ (Morlet). The colours in the wavelet cross-scalograms between w and c denote the flux intensity, where warm colours indicate the highest flux contributions.

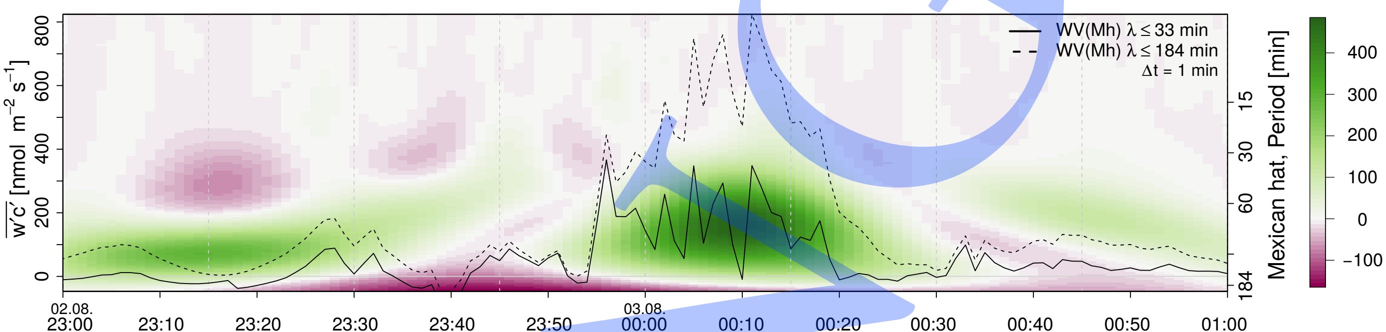

Figure 5. ~~Wavelet~~ Mexican hat wavelet cross-scalogram for the ~~period 02.08.14, 11:00pm – 03.08.14, 1:00am~~ the case study event on 02/03 August 2014 at tower ~~1 for Morlet (top) and Mexican hat wavelets (bottom).~~ 1. The right axis numbers the period, while plotted lines refer to the left axis. Solid lines show the flux for an integration over all periods from $\lambda = 2 \cdot \delta t$ to $\lambda = 33\,\mathrm{min}$ (Mh / Mexican hat)~~and $\lambda = 34\,\mathrm{min}$ (M / Morlet)~~, while the dashed line gives the flux up to $\lambda = 184\,\mathrm{min}$~~(Mexican hat) and $\lambda = 190\,\mathrm{min}$ (Morlet)~~. The colours in the wavelet cross-scalograms between w and c denote the flux intensity, where ~~warm~~ intensive colours indicate ~~the highest~~ higher flux contributions downwards (negative, dark red) or upwards (positive, green).

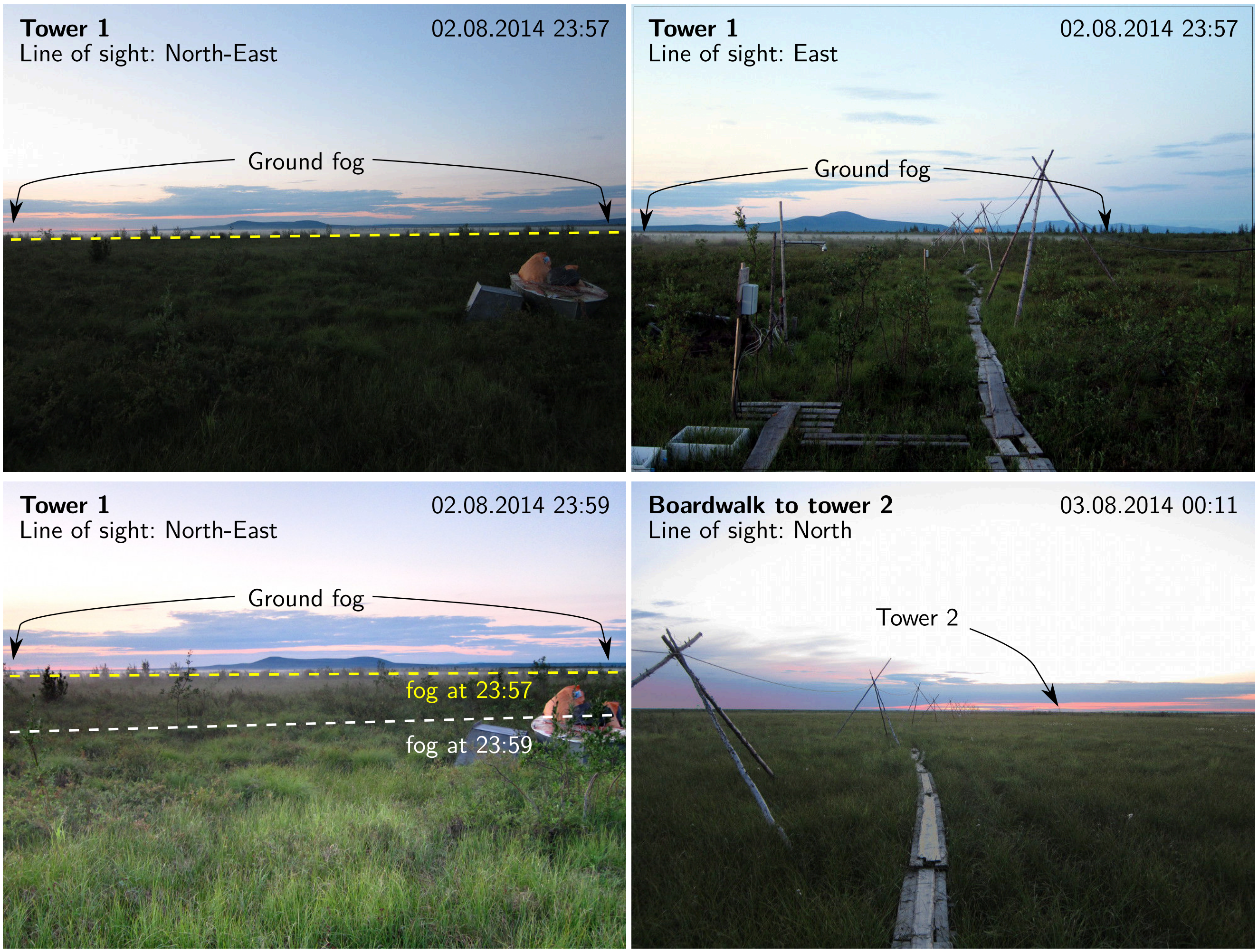

Figure 6. Photos of the study site directly at tower 1 (top and bottom left) and on the boardwalk between the power station at Ambolyka river and tower 2, taken between ~~2 Aug~~ 02 August 2014, ~~11~~23:~~57pm~~ 57 and ~~3 Aug~~ 03 August 2014, 0:~~11am.~~11.

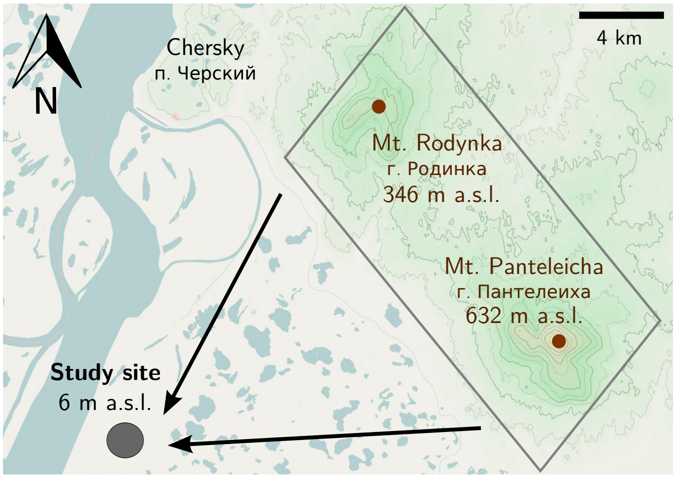

Figure 7. Flow path span of potential cold air drains from the ridge between Mount Rodynka and Panteleicha through the flat floodplains of Kolyma river to the study site (Map modified from www.openstreetmap.org (2015-06-24), copyright by OpenStreetMap contributors under Creative Commons License CC-BY-SA).

Table 1. Mean flux rates during the 30-minute period that hosted the peak event discussed in the case study, as detected by three two different flux processing approaches. All flux values are given in $\mathrm{nmol\,m^{-2}\,s^{-1}}$.

Approach	**Tower 1**	**Tower 2**
Eddy-covariance Eddy covariance	161	213
Mexican Hat hat wavelet	109	179
Morlet wavelet	74	147

Table 2. Night time frequency (21:00 – 9o'clock:00) of the wind directions over the whole measuring period for both towers in percent. The last row gives the frequency of wind directions observed for nighttime peak events. Percentages greater than 20 % are underlined.

Wind sector	**N**	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**
Tower 1	<u>25.3</u>	8.1	8.1	<u>29.2</u>	8.7	3.6	4.5	12.4
Tower 2	<u>25.2</u>	8.3	7.2	<u>28.2</u>	8.7	4.1	4.8	13.6
During events	13.3	<u>20.0</u>	<u>30.0</u>	3.3	0.0	10.0	6.7	16.7