Interactive comment on “Effects of interannual variability in snow accumulation on energy partitioning and surface energy exchange in a high-Arctic tundra ecosystem” by C. Stiegler et al.

Anonymous Referee #2

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In this study the authors assess the impact of strong inter-annual variability in snow accumulation during two subsequent years (2013, 2014) on the land-atmosphere in-teractions and surface energy exchange in two well instrumented high-Arctic tundra ecosystems under different moisture regimes (wet fen and dry heath) in Zackenberg, Northeast Greenland. The study takes advantage of the natural laboratory conditions of strongly different snowcover regimes between the two years, which motivates this study.

Their results suggest that in a changing climate with higher temperature and more precipitation the surface energy balance of this high-Arctic tundra ecosystem may ex-perience a further increase in the inter-annual variability of energy accumulation, partitioning and redistribution.

I think the experimental setup is nice and clear with two differing ground moisture regimes being complemented by two strongly different snowcover regimes. In addi-tion the paper is well organised and clear with precise method descriptions and a clear analysis. The paper is quite straightforward, primarily describing and interpreting the meteorological measurements in the context of their experimental setup and through seasonal changes (polar night, snowmelt, growing season). Due to the paucity of such measurements in the high Arctic this study is an important contribution to knowledge about atmosphere-surface dynamics in the high Arctic and recommend publishing sub-ject to a few minor comments below.

COMMENTS

1. p.2 l.28– You need to mention the two site setup early in this paragraph as you just drop ’at our two high-Arctic sites’ in at the end rather unexpectedly.

- *The paragraph was updated according to the reviewer’s comment (p. 2 l. 19).*

2. P.4 l.6 : this snow depth measurement comes from the Asiaq station or is made directly at the tower? If at the tower what’s the instrument? If at the Asiaq station can you comment on representativeness?

- *Snow depth measurements were conducted at both sites (fen and heath), using snow depth sensors (SR50A, Campbell Scientific, USA). The structure of the paragraph was changed updated with information on snow depth sensor (p. 4, l. 12-16).*

3. p.4 l.14 can you mention the soil depths you measured at?

- *The paragraph was updated with information on measurement depths of the soil temperature (2, 10, 20, 40, 50 and 60 cm), soil heat flux (4 cm depth) and net radiation (3 m height) (p. 4, l. 12-16).*

4. I wasn't able to identify which model OTT pluvio you used based on the reference (p.4 l.17).
    - *The sensor model was updated in the manuscript (52203, R. Young Company, UK) (p. 4, l. 18).*

5. 5. How do you power your stations? Particularly during the polar night?
    - *Power supply for all stations was provided by diesel generators from the nearby Zackenberg Research Station (May to October), and solar panels and a wind mill (Superwind 350, superwind GmbH, Germany) during the period when the research station was closed. The information was added to the manuscript (p. 4, l. 21-22).*

6. Perhaps a parameter table would be a useful look up for this paper with categories of: units, measured/derived, location, instrument (if measured), temporal resolution etc.
    - *A parameter table was added to the manuscript (Table 1).*

I found the last paragraph of Methods (p.6 l.1-10) where you define the "seasons": polar night, melt and growing a little disconnected. Obviously, you organise your results according to these categories which I think is nice, but you could add to this description that this is how you will present the data and why this is informative. This would make the 'story' flow a little better.
- *The paragraph was restructured according to the reviewer's comment (p. 6, l. 4-11).*

8. I feel like the conclusions are missing some kind of outlook to what next ie. integrating models to scale results/ investigate other aspects of the enrgy balance or strategies to reduce the energy balance closure problem. I think a few sentences reflecting on ways of building on this study with further work would be useful.
    - *The conclusions were updated with outlook and importance of extreme events for modelling purposes and the paper's possible contribution to such modelling tools (p. 15, l. 6-15).*

9. Figure 1a: can you mark the Asiaq station on the map?
    - *The figure was updated with the location of the Asiaq-station (see Figure 1a).*

10. Figure 2: mention which site this is in the caption.
    - *The figure caption was updated according to the reviewer's comment (see Figure 3).*

11. Picking up on the comments of J . McFadden and while I agree the stacked plots (Figure 3a/b) make it tricky to identify trends in individual years - I think the key point the authors intend to show is the cumulative energy inputs from all components. If that's the intention I would say some form of cumulative presentation is important.
    - *The design of the figures was updated to ensure a better readability (see Figure 4).*

12. Not immediately obvious which lines the axis refer to in Figure 6b - soil moisture is indicated on the black line, perhaps can do the same with blue/red lines (evaporation?).
    - *The figure was updated to ensure a better readability (see Figure 8).*

Interactive comment on “Effects of interannual variability in snow accumulation on energy partitioning and surface energy exchange in a high-Arctic tundra ecosystem” by C. Stiegler et al.

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This is useful contribution to the arctic surface flux observation literature as the study documents a nice case study of control of the amount of snow (snow depth) on the subsequent evolution of the turbulent surface fluxes and melt. As such, and also given the amount of work it involves to get the data in such an environment, it deserves to be published. I do have some comments however, some major, some minor, that I hope may improve the paper.

Main comments.

First. The paper contains an awful lot of numbers, and no error estimates at all. In the table the SD is given, but if that would be a good measure (and we know it is not), most of the data would fall within the same probability distribution. My first suggestion would be to abandon the use of SD and give the range, and give an error estimate of all your measurements. That helps to assess the significance of your difference.

- *The tables in the manuscript were updated with information on range and error estimates for all the measured parameters (see Table 2-4). Error estimates were considered in the discussion of the revised version of the manuscript (p. 11, chapter 4.1) .*

Second. The energy balance closure is vital to the whole exercise in calculating the amount of energy available for melt as a residual from the energy balance. While I agree that a considerable amount of variability is expected, a value of 67% is very low and needs a little more explaining that referring to site heterogeneity. To show the valid-ity of the eddy covariance measurements I would suggest to include a spectral analysis of the measurements. A good co-spectrum adds to the reliability and acceptance of the data. I also suggest to include this analysis in the description of the methodology, where it belongs, and not include as as an afterthought in the discussion.

- *Sample analysis of cospectra were performed for both sites (p. 4, l. 9-11). The results and discussion of this analysis was added to the manuscript (p. 12, chapter 4.2). Previous cospectra analysis have been performed at the two study sites, showing high-frequency loss of data. However, the range of the high-frequency loss is consistent with values observed from other studies using the same instrumental setup. The information was added and discussed in the manuscript (p. 12, l. 9-20).*

)
Third. Soil moisture. In terms of controlling factors, soil moisture is the key term that controls the partitioning of the energy budget terms. Precipitation and snow depth are just proxies in that sense. I am surprised that only in Figure 6 soil moisture is used. In fact how it is measured is not mentioned at all in $ 2.2. Was it only measured at the dry heath. Please explain and use the data!

- *Soil moisture was only measured at the dry heath since the wet fen is characterized by constant water-saturation. Information on soil moisture sensor and measurement depth is added to the methods section (see chapter 2.2, p. 4, l. 15-16).*

Fourth. Overall the analysis is very descriptive, even lacklustre at times. This is a pity as the data are very valuable! For example when parameters like surface resistance of omega are calculated there is no real effort to explain or interpret these (I find the big difference between the yearly wet fen values somewhat worrying though, given the magnitude of the difference; even between different vegetation types you would not expect such a big difference). This really needs some work. For instance if a wetter Arctic would imply less H, would that provide a negative feedback on the warming trend? There are plenty of such questions to ask given the data and I encourage the authors to think these through and by doing so add more meat to the discussion. I am also surprised to find that there is no mention of the Kasurinen et al., 2014, GCB study at all, given some of the co-authors participated in that study. This does provide a very useful benchmark for the present study.

- *Values of surface resistance were recalculated and checked for their reliability. In the discussion section (chapter 4.2, p. 14, l. 5-17), a paragraph describing possible reasons for the observed differences in surface resistance, omega and Bowen ratio between the two years was added, considering additional literature such as Kasurinen et al., 2014, Lafleur & Rouse, 1988, etc (p 14, l. 5-17)*

Fith. I would rephrase the title to make it a better aligned with the content. Something like a “A comparison of surface energy budgets of : : : in two years with extreme and little snowfall”.

- *The title was rephrased. “Two years with extreme and little snowfall: Effects on energy partitioning and surface energy exchange in a high-Arctic tundra ecosystem”.*

Minor comments

P1 l10. The use of interannual suggest that many years are used. I would suggest to not use this word and stick to the comparison of a snow rich and snow poor year (see above remark on title as well).

- *The word “interannual” was omitted in the context of the manuscript.*

P3 l27-30. This should be part of the introduction, not site description.

- *The part was moved to the introduction.*

P4 $2.2 Measurements. Have the systems be run side by side in a comparison experiment to show that they provide the same fluxes when at the same site? What are otherwise the errors you expect in the fluxes?

- *No direct comparison experiment of the two systems have been performed. However, we use well-applied sensors and processing schemes which follow the general standards and requirements of ICOS. Measurement errors due to technical sensor specifications at the two sites are therefore considered to be negligible. The information was added to the manuscript (p. 3, l. 29-31, p. 4, l. 9-11).*

P5 l11-13. Is there a way you can quantity the error that this would generate on your estimates of energy available for melt.

- *We lack information on snow density during that winter. Further, we have no sensors measuring the snowpack temperature when the snow cover is <10 cm. Therefore, we were not able to correct G for storage within the snow pack. However, we assume that heat storage in the snow layer was negligible during that winter, with only little impact on the total energy available for snow melt. The information was added to the manuscript (p. 6, l. 13-15, p. 12, l. 5-8).*

P6 l28-30. I would guess that synoptic variability and weather dynamics also play a role here. You are expressing an extreme 1-D view of the atmosphere here.

- *The paragraph was restructured (p. 7, l. 7-12).*

P7 28-29. This is an example of my first major comment. Are these values really different, or do they fall within you measurement error (given your energy closure for instance)?

- *The related table 3 was updated with information on range and error estimate for the specific parameters.*

P8 l16 gives an another example.

- *The related table 3 was updated with information on range and error estimate for the specific parameters.*

P8 l26-27. Is there any way you can relate this to greenness, density of vegetation as well, or is this really just an effect of the relative contribution of snow versus vegetation. I am asking also in relation to Fig 1, where a different colour seems to be visible for the different years.

- *The paragraph was updated with information on NDVI measurements from the wet fen site (p. 4, l. 20-23, p. 9, l. 12-13).*

p9. $3.3.4. This part really needs some more work and check on the values of Rs in the dry heat growing season. Also it may be better to define a period of maximum gs, rather that show the average which is biased by the shoulder values of the season. Reference here also Kasurinen et al, 2014. This part is presently pretty shallow, I am afraid to say.

- *In the discussion section (see chapter 4.1 and 4.2) we added a paragraph focussing on the interpretation of the presented data (p. 12, l. 4-20).*

P12 l27. I guess you mean soil moisture rather than groundwater? Otherwise how did you determine this?

- *The paragraph was updated to “minerotrophic water supply”, p.*

Figure 3a and 3b. Can you add the snowmelt of 3b just to 3a? This avoids repetition of the albedo and snow depth and temperature plot. You adjust the time period to the longer one of 3b.

- *All figures (see Figure 1-9) were updated to provide a better readability.*

Figure 5. Can you reduce the scale of the Y-axis in the lower panel plots so that differences are more visible?

- *The figure was updated according to the reviewer’s comment (see Figure 6).*

Figure 6. Can you add a second y-axis that gives the % of use of available energy for the different fluxes?

- *The figure was updated according to the reviewer’s comment (see Figure 7).*

Figure 6b is confusing as it does not fit with 6a (it shows both the dry tundra and wet fen and both years) and the structure of all the other plots. Make it a separate plot.

- *The figure was updated according to the reviewer's comment (see Figure 7 and 8).*

Interactive comment on “Effects of interannual variability in snow accumulation on energy partitioning and surface energy exchange in a high-Arctic tundra ecosystem” by C. Stiegler et al.

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This paper reports results from a 2-year field measurement campaign at Zackenberg, Greenland to measure seasonal time series of energy budget components in two con-trasting arctic vegetation types, wet fen and dry heath tundra. The paper makes use of the fact that there was a strong contrast in snow cover between the two years to infer what changes in surface energy exchange might be expected under a warming (and higher precipitation) arctic climate. Changes in the arctic energy budget, especially those studied seasonally, are important. The variety of ecosystem types that have been measured–including in Greenland–is relatively few, making this an important contribu-tion to our knowledge of cold land processes. The manuscript is very clearly written, well organized, and the data are well presented (but see a few comments below). The conclusions are reasonable and are supported by the data. I recommend the paper for publication with only minor revisions. In my view, the paper is very good and the detailed comments below are given as constructive suggestions to improve the final version.

General comments:

1) Figure design. The figures are very nice and clearly labeled; however, some of them are confusing to read. For example, in Figs 3a and 3b the stacked bar plots make it very hard to see the differences between sites and years. Stacked bars are difficult in general, but the large difference in the size of the trends (e.g. the tiny negative values of Rnet) make it really difficult to discern, especially in these small panels. I think the data will come across to the reader better and the paper will have better impact if you can find another way to show these data. Maybe it would be a non-stacked bar plot, a line plot, or something else. Maybe they need to be made larger so that you show only one vegetation type at a time. I understand the reasons why you laid out the panels as you did, it’s just that they end up difficult to read and so the result will be better if you can revise them to show the various data values more clearly.

- *All figures were updated (see Figures 1-9).*

Secondly, the use of color is not always allowing the reader to quickly pick out what is what. Sometimes the colors are inconsistent, for example in Fig 5, H and LE are shown in red and blue, and G is in green. But in Fig 6, H and LE follow the same red and blue style, but G is now in gray. Earlier in the paper (Figs 3a and 3b), the same shades of red and blue are used instead for albedo and snow depth. I think you might be better off to remove color from most of the plots where it is possible, and reserve the use of color only where it is the best/only way to show the differences. For example, you could symbolize albedo and snow depth with black lines of different thicknesses, or using dashes. I would suggest placing all of the color figures all together out on a table and then deciding on a system so that the same type of color or symbols are used consistently, and simplify them as much as you can by not using color at all unless it is needed.

- *Figure design and colour regime was updated, using the same or similar colour regime for each parameter in the different figures (see Figures 2-8).*

2) References. The paper does a good job of citing relevant literature overall, but its impact would be improved by making more direct comparisons to other arctic energy budget studies, especially those outside of Greenland. There are still few enough such studies that this is valuable to the scientific community to provide a bigger context for your findings. The manuscript did cite the big review paper of Eugster et al. (2000), but you didn’t use that paper to actually compare the energy budget patterns you found to the patterns reported for other arctic ecosystems. At least in the North American Arctic where I have worked, there are other studies that have measured the same energy budget components and even looked at some of the same wet-dry ecosystem comparisons as you are making here. I think the paper would be stronger if it linked into the Arctic literature a little better by directly stating whether the results obtained here are consistent with or different from the values and the overall patterns found in a broader set of arctic sites. This need not be a major addition to the text, but just digging in a bit deeper for each such value or pattern that you highlight in the Discussion.

- *The discussion section (see chapter 4.1 and 4.2) was updated by comparing our measurements with studies from Siberia (Boike et al., 2008), other arctic locations (Sturm and Douglas, 2005; Kasurinen et al., 2014) and previous measurements at the study site (Lund et al., 2014, Soegaard et al., 2001).*

Detailed comments:

Abstract. The last part of the final sentence in the abstract is rather vague. Simply "increasing interannual variability" seems rather general and less interesting that what you actually found. I suggest thinking about how your could "sharpen" this final state-ment to make it more specific and impactful. I could imagine you might want to say something about how interannual climate variability (winter precip) has been shown to have different feed backs to surface energy partitioning depending on ecosystem type...

- *The final section of the abstract was rephrased, focussing on the different effects of ecosystem type and surface properties on surface energy balance.*

p 4, Measurements. Accepted that you are using standard CarboEurope type proce-dures, but can you add a citation to a paper from your flux site that explains site-specific procedures and conditions? If not, then can you please add just a brief description of key site specific information such as how data were screened (spikes, low turbulence, unfavorable meteorological conditions) and how many gaps (what percentage of the record, what percentage of the daytime values that went into the energy budget mea-surements, or whatever you think is relevant)? I see that you later explain that you used the MPI online gap-filling tool to do the gap filling. I am just requesting a little info to characterize data screening and the overall situation with gaps at the two towers. And any other key, site-specific information or procedures that you think are important to the reader. If all of this is summarized in a different flux paper, then it is fine to simply cite it as above, and say that those details are provided in the cited paper.

- *Data processing for both study locations is summarized in Soegaard et al., 2001 and Lund et al. (2012, 2014). The sentence was added to the paragraph (p. 4, l. 6-11).*

p 7, line 10-11: It is very difficult to see the negative values of Rnet in the figure because of its vertical scale and the bar type. Please see general comment above on the figures.

- *The figure was updated (see Figure 4).*

p 8, line 6ff: Please provide a short sentence or two explaining how the 2 study years compare to the long-term climate of the site. Which of the study years was more typical of "mean" climate conditions for this location in terms of the different seasons and meteorological variables? Which aspects were most atypical–only the low-snowfall year, or anything else?

- *The paragraph was updated with information on mean climate conditions for this location and how the two study years compare to the long-term climate of the area (p. 8, l. 17-26).*

p 12, line 4: Recommend changing "shields off" to "reflects".

- *The wording was changed according to the reviewer's comment.*

p 13, Energy Budget Closure section: I suggest that you move the energy budget clo-sure discussion somewhere further up in the Discussion section, rather than as the last item. There are two reasons for this. First, it makes the paper less impactful if the very last item discussed is a technical system-performance assessment like energy budget closure, rather than one of the main findings on your scientific questions. Second, it is arguable that the reader should know whether you think the energy closure imbalance is typical of arctic sites or is in any way a problem before reading onward to the main scientific findings. You might even put it first in the discussion, or at least somewhat closer to the begining of the discussion, and not the very last item.

- *The section on energy budget closure was put first in the discussion (see chapter 4.1).*

In addition, do you think that variations in the depth of permafrost may have been a source of uncertainty/error in estimating the ground heat flux and energy budget closure, and if yes, you could mention that.

- *Information on the impact of permafrost and soil thermal gradients on the ground heat flux was added to the discussion section (p. 12, l. 5-8).*

Finally, I suggest that you end the part about energy budget closure with a comment on how the lack of closure would (or would not) affect your findings. For example, you may believe that the H and LE fluxes are OK and that the closure error is mostly in G. Rn is not affected, and so forth. I think it would make the paper stronger if you could provide a short sentence or 2 at most that interprets what the closure error means for the results you have obtained here.

- *The discussion section was updated with additional information on the accuracy of turbulent heat fluxes and the overall system performance (see chapter 4.1).*

p 14, line 8: Change "discusses" to "discussed"

- *The wording was changed.*

Some other arctic energy budget references (not exhaustive, just some close examples to what you have done here)

Sturm, M., et al. (2005). "Changing snow and shrub conditions affect albedo with global implications." Journal of Geophysical Research-Biogeosciences 110(G01004).

McFadden, J. P., et al. (2003). "A regional study of the controls on water vapor and CO2 exchange in arctic tundra." Ecology 84(10): 2762-2776.

McFadden, J. P., et al. (1998). "Subgrid-scale variability in the surface energy balance of arctic tundra." Journal of Geophysical Research 103(D22): 28947–28961.

Rouse, W. R. (2000). "The energy and water balance of high-latitude wetlands: con-trols and extrapolation." Global Change Biology 6: 59–68.

Lafleur, P. M. and W. R. Rouse (1988). "The influence of surface cover and climate on energy partitioning and evaporation in a subarctic wetland." Boundary-Layer Meteorol-ogy 44(4): 327–348.

Lafleur, P. M., et al. (1987). "Components of the surface radiation balance of sub-arctic wetland terrain units during the snow-free season." Arctic, Antarctic, and Alpine Research 19(1): 53–63.

- *Additional literature was included into the manuscript.*

<u>Two years with extreme and little snowfall: </u>Effects ~~of interannual variability in snow accumulation~~ on energy partitioning and surface energy exchange in a high-Arctic tundra ecosystem

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Abstract. Snow cover is one of the key factors controlling Arctic ecosystem functioning and productivity. In this study we assess the impact of strong ~~interannual~~ variability in snow accumulation during two subsequent years (2013-2014) on the land-atmosphere interactions and surface energy exchange in two high-Arctic tundra ecosystems (wet fen and dry heath) in Zackenberg, Northeast Greenland. We observed that record-low snow cover during the winter 2012/13 resulted in strong response of the heath ecosystem towards low evaporative capacity and substantial surface heat loss by sensible heat fluxes (*H*) during the subsequent snow melt period and growing season. Above-average snow accumulation during the winter 2013/14 promoted summertime ground heat fluxes (*G*) and latent heat fluxes (*LE*) at the cost of *H*. At the fen ecosystem a more muted response of *LE*, *H* and *G* was observed in response to the ~~interannual~~ variability in snow accumulation. Overall, the differences in flux partitioning and in the length of the snow melt periods and growing seasons during the two years had a strong impact on the total accumulation of the surface energy balance components. We suggest that in a changing climate with higher temperature and more precipitation the surface energy balance of this high-Arctic tundra ecosystem may experience a further increase in the ~~interannual~~ variability of energy accumulation, partitioning and redistribution.

1 Introduction

The presence or absence of snow exerts a strong impact on the land-atmosphere interactions and on the exchange of energy and mass. The high albedo of snow (Warren, 1982) reduces the amount of absorbed shortwave radiation at the surface which generally leads to a smaller magnitude of the surface energy balance components. The influence of the snow on the energy balance is most pronounced during spring when the commonly patchy distribution of snow causes strong spatial variations in surface temperature and surface energy balance components (Chernov, 1988). The meltwater in Arctic soils contributes a considerable proportion of plant available water during summertime and as such, end-of-winter snow depth constitutes an important control of the summertime energy partitioning into sensible and latent heat fluxes (Langer et al., 2011).

Since the end of the Little Ice Age the climate in the Arctic has undergone a substantial warming to the highest temperatures in 400 years (Overpeck et al., 1997). Warming has further accelerated during the second half of the 20th century and almost doubled compared to the rest of the globe (Stocker et al., 2013). Between the years 1966 and 2003 temperatures in the Arctic increased by 0.4°C per decade with most pronounced warming during the cold seasons (McBean et al., 2005). A reanalysis of meteorological observations over the period 1989-2008 shows that near-surface warming is 1.6°C during autumn and winter and 0.9°C and 0.5°C during spring and summer (Screen and Simmonds, 2010). It is suggested that diminishing sea ice, snow- and ice-albedo feedbacks and atmospheric energy transport into the Arctic govern Arctic temperature amplification (Graversen et al., 2008; Screen and Simmonds, 2010; Bintanja and van der Linden, 2013)

Precipitation in the Arctic is generally low, however, for the period from 1900 to 2003 precipitation increased by 1.4% per decade (McBean et al., 2005) with a pronounced increase mostly during winter (Becker et al., 2013). The observed contribution of snow precipitation to total annual precipitation has declined (Hartman et al., 2013). Extreme events such as extremely high temperatures and heavy precipitation have increased while extremely low temperatures have decreased over most parts of the Arctic (Hartman et al., 2013). During the 21st century the ongoing changes in the temperature and precipitation regime are expected to continue. By the end of the century, models based on the Representative Concentration Pathways (RCP) 4.5 scenario predict an average warming of 3.9°C over Arctic land areas (Stocker et al., 2013) and an increase in precipitation of more than 50%, mostly during autumn and winter (Bintanja and Selten, 2014). However, due to the increase in air temperature and rain-on-snow events the maximum amount of snow accumulation on the ground is projected to increase by only 0-30% and snow cover duration might decrease by 10-20% over most of the Arctic regions (Callaghan et al., 2011a).

At our study region in Zackenberg, Northeast Greenland, ~~During the period 2000-2010~~ mean July air temperatures ~~in the Zackenberg area~~ during the period 2000-2010 increased by 0.18°C yr^{-1} and active layer thickened by 1.5 cm yr^{-1} (Lund et al., 2014). Based on the IPCC SRES A1B scenario (Nakićenović et al., 2000), local climate modelling for the region predict an increase in mean annual air temperature by 4.1°C for the period 2051-2080 compared to 1961-1990 with highest increase during winter (6.6°C) and spring (7.4°C) while precipitation over eastern Greenland is projected to increase by 60% (Stendel et al., 2007).

Arctic ecosystems are highly adapted to extreme seasonal variability in solar radiation, temperature, snow cover and precipitation. However, studies have shown that winter warming events and interannual snow cover variability affect ecosystem functioning in various adverse ways and these extremes are expected to occur more frequently in the future (Callaghan et al., 2005; Kattsov et al., 2005; Stocker et al., 2013). Hence, there is an urgent need to assess their impact on Arctic ecosystems. Several studies have focused on the effect of extreme temperatures on plant productivity and carbon sequestration (Chapin III et al., 1995; Marchand et al., 2005; Euskirchen et al., 2006; Bokhorst et al., 2008; Bokhorst et al., 2011) but the direct impact of successive ~~and interannual~~ snow cover variability on the land-atmosphere interactions and surface energy balance components is largely unknown.

Here we examine the impact of strong ~~interannual~~ variability in snow accumulation by studying the land-atmosphere interactions and surface energy balance components in a high-Arctic tundra heath and fen environment during two subsequent years (2013-2014) with distinct differences in end-of-winter snow depth. Our study area is located in Zackenberg in Northeast Greenland where record-low snow accumulation was observed during the winter 2012/13 (Mylius et al., 2014), followed by snow-rich conditions during the winter 2013/14. This sequence of strong variability in snow accumulation forms the following objectives of our study: (1) To assess the magnitude of the energy balance components and moisture exchange during the snow melt periods and growing seasons in 2013 and 2014, and (2) to quantify and evaluate the driving factors of surface energy partitioning during the observation period at our ~~two~~ high-Arctic fen and heath site~~s~~.

2 Materials and methods

2.1 Study sites

The study sites are located in the valley Zackenbergdalen in Northeast Greenland near the Zackenberg Research Station (74°30'N, 20°30'W) (Fig. 1a). The valley is surrounded by mountains to the west, north and east while the Young Sound and Tyrolerfjord form the valley boundary to the south. Vegetation is sparse and mainly found in the valley bottom and on the lower parts of the slopes. *Cassiope* heaths, *Salix arctica* snow-beds, grasslands and fens with sedges and grasses dominate in the lowlands while open *Dryas* sp. heaths and grasslands form the main plant communities on the slopes (Bay, 1998).

We conducted measurements of surface energy balance components and meteorological variables in a wet fen and in a tundra heath, with a distance of approx. 600 meters between the two measurement towers. The fen area can be divided into a continuous fen, with flat areas dominated by *Eriophorum scheuchzeri*, *Carex stans* and *Duponita psilosantha*, and a hummocky fen dominated by *E. triste*, *S. arctica* and *Andromeda latifolia* (Bay, 1998; Elberling et al., 2008). The tundra heath site is characterized by *Cassiope tetragona*, *D. integrifolia*, *Vaccinium uliginosum* and patches of mosses, *E. scheuchzeri* and *S. arctica* (Lund et al., 2012).

Since August 1995 meteorological and environmental monitoring activities have been conducted by the Zackenberg Ecological Research Operations (ZERO), a part of the Greenland Ecosystem Monitoring (GEM) programme. Mean annual air temperature in Zackenberg (1996-2013) is -9.0°C, with an average span from -19.3°C in January to +6.3°C in July (Mylius et al., 2014). Annual precipitation is low (211 mm) (Mylius et al., 2014) and approx. 85% consists of snow precipitation (Hansen et al., 2008). Snow cover is unevenly distributed in the valley with large deposits on south-facing slopes as winds from the north (offshore) dominate during the winter (Soegaard et al., 2001). During the growing season winds from south-east (onshore) are dominating (Elberling et al., 2008). The area is located within the zone of continuous permafrost and active layer thicknesses at the end of the summer reach between 0.4 and 0.8 m within the valley (Christiansen, 2004; Pedersen et al., 2012).

~~During the period 2000-2010 mean July air temperatures in the Zackenberg area increased by 0.18°C yr^{-1} and active layer thickened by 1.5 cm yr^{-1} (Lund et al., 2014). Based on the IPCC SRES A1B scenario (Nakićenović et al., 2000), local climate modelling for the region predict an increase in mean annual air temperature by 4.1°C for the period 2051-2080 compared to 1961-1990 with highest increase during winter (6.6°C) and spring (7.4°C) while precipitation over eastern Greenland is projected to increase by 60% (Stendel et al., 2007).~~

2.2 Measurements

Fluxes of sensible (*H*) and latent heat (*LE*) at the wet fen and the dry heath were measured by two eddy covariance systems. Standard flux community instrumentation and processing schemes were used to ensure reliable data quality. The eddy covariance system at the wet fen, e.g., uses well-accepted measurement standards of ICOS (Integrated Carbon Observation System). At the wet fen a 3 m tower was equipped with a LI-7200 (LI-COR Inc., USA) enclosed-path gas analyser and a Gill HS (Gill Instruments Ltd, UK) 3D wind anemometer. Air was drawn at a rate of 15 L min^{-1} through a 1 m long tube (9 mm inner diameter). Data from both sensors was sampled at a rate of 20 Hz and fluxes were calculated using EddyPro software (LI-COR Inc., USA)~~. Snow depth measurements were used to dynamically estimate sonic height above the snow layer~~. Air temperature (T_a), relative humidity (*RH*) and air pressure measured by external sensors was used in flux calculations. The gas analyser was calibrated based on manual calibrations using air with known CO_2 concentration and based on estimated H_2O concentration from T_a/RH measurements. Post-processing and quality checks follow standard procedures (Aubinet et al., 2012).

At the dry heath a 3 m tower was equipped with a Gill R3 (Gill Instruments Ltd, UK) sonic anemometer and a LI-7000 (LI-COR Inc., USA) gas analyser. Air was drawn through 6.2 m of tubing (inner diameter: 1/8'') at a rate of 5.5 L min^{-1} to the sensor. To ensure that the eddy covariance measurements capture all scales of mixed-layer turbulence, cospectral analysis (Wyngaard and Cote, 1972) between the vertical wind velocity and turbulent energy flux was performed at both study locations. Data processing for both study locations is further summarized in Soegaard et al., 2001 and Lund et al. (2012, 2014). ~~More information on the eddy covariance system and data processing is provided by Lund et al. (2012, 2014).~~

At both locations snow depth measurements (SR50A, Campbell Scientific, USA) were used to dynamically estimate sonic height above the snow layer and soil temperature (T107, Campbell Scientific, USA) at a depth of 2, 10, 20, 40, 50 and 60 cm~~various depths~~, soil heat flux (HFP01 Hukseflux, The Netherlands) at a depth of 4 cm, ~~and~~ net radiation (CNR4 Kipp & Zonen, The Netherlands) at a height of 3 m and snow pack temperature at 10, 20, 40, 60, 90 and 120 cm above the soil surface were measured. At the dry heath, soil moisture (SM 300, Delta-T Devices, UK) was measured at a depth of 5, 10, 30 and 50 cm.

Ancillary meteorological parameters such as ~~snow depth (SR50-45, Campbell Scientific, USA),~~ air temperature and humidity (HMP 45D, Vaisala, Finland), radiation components (CNR1, Kipp & Zonen, The Netherlands) and precipitation (52203, ~~5915 x, OTT Hydromet GmbH~~R. Young Company, ~~Germany~~USA) are provided from a nearby meteorological station operated by Asiaq – Greenland Survey. This station is located at the same heath, approx. 150 m away from the heath eddy covariance tower. Normalized Difference Vegetation Index (NDVI) was measured at the wet fen site (SKR 1800, Skye Instruments Ltd, UK). Power supply for all stations was provided by diesel generators from the nearby Zackenberg Research Station (May to October), and solar panels and a wind mill (Superwind 350, superwind GmbH, Germany) during the period when the research station was closed.

2.3 Data analysis and derived parameters

The surface energy balance of the wet fen and the dry heath is described by:

$$R_{net} = H + LE + G + E_{melt} \tag{1}$$

where R_{net} is the net radiation, H is the sensible heat flux, LE is the latent heat flux, G is the ground heat flux at the soil or snow surface, and E_{melt} is the energy flux used for snow melt (Table 1). During the snow-free season E_{melt} is zero. The left side of the equation represents the system's gain of energy and the right-hand side represents the losses of energy. Bowen ratio (H/LE) and ratios of H/R_{net}, LE/R_{net} and G/R_{net} are used to characterize relative magnitude of the heat transfer from the surface.

The net radiation balance (R_{net}) was defined as:

$$R_{net} = RS\downarrow - RS\uparrow + RL\downarrow - RL\uparrow \tag{2}$$

where $RS\downarrow$ and $RS\uparrow$ are incoming and outgoing shortwave radiation, and $RL\downarrow$ and $RL\uparrow$ are upwelling and downwelling longwave radiation, respectively. Surface albedo was calculated as the quotient between $RS\downarrow$ and $RS\uparrow$. Missing values from radiative components at the dry heath site were filled with measurements from the nearby Asiaq meteorological tower.

Ground heat flux at the soil or snow surface (G) was calculated by adding the storage flux in the layer above the heat flux plate (S) to the measured flux:

$$S = C_s \frac{\Delta T_s}{\Delta t} d \tag{3}$$

where $\Delta T_s/\Delta t$ is the change in soil or snow pack temperature (K) over time t (s), d is the heat flux plate installation depth (m) and C_s is the soil or snow pack heat capacity (J m^{-3} K^{-1}) defined as:

$$C_s = \rho_b C_d + \theta_v \rho_w C_w \tag{4}$$

where ρ_b is the bulk density, C_d is the dry soil heat capacity of 840 J kg^{-1} K^{-1} (Hanks and Ashcroft, 1980) or the heat capacity of ice (2102 J kg^{-1} K^{-1}), θ_v is the volumetric soil or snow pack water content (m^3 m^{-3}), ρ_w is the water density (1000 kg m^{-3}) and C_w is the water heat capacity (4186 J kg^{-1} K^{-1}). For ρ_b a value of 900 kg m^{-3} at the heath and 600 kg m^{-3} at the fen (Elberling et al., 2008) was used during the growing season while during the snow melt period in 2014 the density of the snow pack was derived from in-situ measurements. Since no snow density measurements were performed during the snow melt period in 2013 and the soil surface was not completely snow-covered during that period, G in 2013 was not corrected for heat storage within the snow pack.

The aerodynamic resistance (r_a, s m^{-1}) determines the turbulent heat transfer from the surface and was defined as (Monteith and Unsworth, 2013):

$$r_a = \frac{u}{u_*^2} + 6.2 u_*^{-0.67} \tag{5}$$

where u is the wind speed (m s^{-1}) and u_* is the friction velocity (m s^{-1}).

Surface resistance (r_s, s m^{-1}), as a measure to quantify the stomatal control in the canopy on the turbulent fluxes, was calculated as (Shuttleworth, 2007):

$$r_s = \left(\frac{\Delta}{\gamma}\beta - 1\right) r_a + (1+\beta)\frac{\rho c_p}{\gamma}\frac{D}{A} \tag{6}$$

where Δ is the slope of the saturated vapour pressure curve (Pa K^{-1}), γ is the psychrometric constant (Pa K^{-1}), β is the Bowen ratio, ρ is the air density (kg m-3) c_p is the specific heat capacity of air at constant pressure (J kg^{-1} K^{-1}), D is the atmospheric vapour pressure deficit (Pa) and A is the available energy for evaporation ($R_{net} - G$, W m^{-2}).

The decoupling coefficient (Ω) (Jarvis and McNaughton, 1986) expresses the degree of interaction between r_a and r_s:

$$\Omega = \left(1 + \frac{\Delta}{\Delta+\gamma}\frac{r_s}{r_a}\right)^{-1} \quad (7)$$

The decoupling coefficient varies from 0 to 1 where Ω close to zero indicates a strong coupling between the vegetation and the atmosphere, with vapour pressure deficit (VPD) being the main driver of LE, whereas Ω close to 1 suggest a decoupling of LE and VPD, with R_{net} being the main driver for LE.

Priestley-Taylor coefficient (α) (Priestley and Taylor, 1972) was calculated as:

$$\alpha = \frac{\Delta+\gamma}{\Delta(1+\beta)} \quad (8)$$

Over ocean and saturated land surfaces the dimensionless α equals to 1.26 but fluctuates depending on surface structure and meteorological conditions.

To assess the full impact of differences in snow accumulation on the surface energy exchange the presented results focus on four major subperiods, i.e. polar night, pre-melt season, snow melt period and growing season, which we defined the following: Polar night is

~~Polar night was defined as~~ the time period when the sun is~~was~~ below the free horizon. In Zackenberg, the polar night lasts from 10 November to 4 February (86 days). ~~In our study, the~~The subsequent pre-melt season marks the time period between the polar night and the first day of snow melt. In spring, a steady and constant decrease in daily average albedo and snow cover thickness until snow cover diminished was defined as the snow melt period. The beginning of the subsequent growing season was defined as the time when albedo was lower than 0.2. Positive daily average air temperature and top soil layer temperature (2 cm depth), net radiation >0 W m^{-2} and albedo lower than 0.2 define the growing season.

Gap-filling of the eddy covariance data was performed based on a look-up table approach (Falge et al., 2002; Reichstein et al., 2005) using the REddyProcWeb online tool (Max Planck Institute for Biogeochemistry). Due to very limited data availability at both locations during the second snow melt period in 2014 no gap-filling of H and LE was applied and turbulent fluxes of H and LE were excluded from the analysis during that period.

3 Results

3.1 Energy balance closure

The observed slopes of the regressions between available energy at the surface ($R_{net} - G$) and the sum of the turbulent heat fluxes ($H+LE$) serve as an indicator for the energy balance closure. Figure 2 shows the comparison between mean daily $R_{net} - G$ and mean daily $H+LE$ for the two study sites. The observed slopes at the wet fen are 0.68 during both 2013 and 2014. For the dry heath the slopes are 0.81 (2013) and 0.82 (2014).

3.~~1~~ 2 Polar night and pre-melt season

The pattern of snow accumulation during the polar night and pre-melt season differed strongly between the two winters (Fig. 1b). There was no distinct development of a closed snow cover or major events of snow accumulation during the first winter (2012/13) and by the end of the pre-melt season as little as 0.09 m of snow pack at the wet fen and 0.14 m at the dry heath was present. The second winter (2013/14) showed a similar trend in the beginning of the winter with snow pack thickness of less than 0.1 m until mid-December 2013. After that, a snow pack of 0.8 m developed during two major events of snow fall (17-25 December 2013 and 21-27 January 2014) and by the end of the second winter the snow pack reached a thickness of 1.04 m at the wet fen and 0.98 m at the dry heath (Fig. 3~~2~~).

In the absence of solar radiation during the polar night thermal radiation (RL_{net}) is the sole driver of the surface energy balance (Fig. 3~~2~~). Daily average downwelling longwave radiation ($RL\downarrow$) was 193 W m^{-2} during the first polar winter (2012/13) and 213 W m^{-2} during the second polar winter (2013/14). The corresponding values for the upwelling longwave radiation ($RL\uparrow$) were 219 W m^{-2} and 237 W m^{-2} for the two polar winter periods. The differences in longwave radiation corresponded well with the differences in air and snow surface temperatures. The average air temperature, which mainly controls the downwelling longwave radiation, was -19.2°C and -15.2°C for the two consecutive polar winter periods and the snow surface temperature together with cloudiness, which mainly controls emissivity, was -24.1°C and -19.2°C, respectively. Overall, average RL_{net} was -27 W m^{-2} in 2012/13 and -24 W m^{-2} in 2013/14. The lowest air temperatures (-33.7°C and -33.7°C) and snow surface temperatures (-39.8°C and -39.9°C) for both polar winters, however, were reached shortly after the onset of the pre-melt seasons. In 2013, this coldest period was followed by a foehn event with air temperatures just below -1°C on 7 March. Incoming solar radiation ($RS\downarrow$) showed a continuous increase over the pre-melt season, with higher values observed during the winter 2012/13 compared to 2013/14, mainly driven due to differences in surface albedo.

~~The two subsequent pre-melt seasons were characterized by a continuous increase in incoming solar radiation ($RS\downarrow$) but with little impact on the air and surface temperatures (Fig. 2) due to high albedo. Actually, the lowest air temperatures (-33.7°C and -33.7°C) and snow surface temperatures (-39.8°C and -39.9°C) for both polar winters were reached during this period.~~

3.~~2~~ 3 Snow melt season

At the beginning of the snow melt period in 2013 the vegetation on both sites was not completely snow-covered. Snow melt started on 13 May and lasted until 29 May (17 days) at the wet fen and until 30 May (18 days) at the dry heath. Snow ablation in 2014, however, started 7 days earlier compared to 2013 (6 May) but lasted 28 days longer at the dry heath site (27 June) and 25 days longer at the wet fen site (23 June). Daily average air temperatures remained below 0°C for most of the snow melt periods with average values of -1.8°C in 2013 and -1.3°C in 2014 (Fig. 4~~3~~). High rates of snow ablation after 6 June 2014 coincided with daily average air temperatures >0°C which peaked on 16 June 2014 with 9.6°C.

During the snow melt period in 2013, albedo decreased gradually from about 0.76 in the beginning of the period down to 0.15 for the wet fen and 0.10 for the dry heath (Fig. 4~~3a~~). The decrease in albedo happens simultaneously with a continuous increase in net radiation (R_{net}) (Fig. 4 ~~3a~~). However, while daily average R_{net} remained negative for most of the first half of the snow melt period in 2014 (Fig. ~~3b~~4), positive values dominated the entire snow melt period in 2013. Substantial differences in albedo cause these variations, especially in the beginning of the snow melt seasons when daily average albedo was >0.60. During that period, average albedo at both sites was 0.71 in 2013 and 0.79 in 2014. These differences in the surface characteristics reduced average R_{net} in 2014 by 4.1 W m^{-2} although incoming solar radiation ($RS\downarrow$) was 87.0 W m^{-2} higher compared to 2013. By the end of the snow melt period in 2013, R_{net} accumulated 76.1 MJ m^{-2} at the dry heath and 94.3 MJ m^{-2} at the wet fen. The corresponding values for 2014 were 174.5 MJ m^{-2} and 202.9 MJ m^{-2}, respectively. Due to the lower albedo during the first snow melt season the soil experienced a faster spring warming compared to 2014. Top-soil layer temperatures (T_{surf}) at the dry heath increased by 0.41°C d^{-1} in 2013 and 0.28°C d^{-1} in 2014. At the wet fen, the warming of the soil was 0.35°C d^{-1} in 2013 and 0.28°C d^{-1} in 2014.

Daily average sensible heat flux (H) was small and negative (-4.1 W m^{-2}) during the first ten days of the snow melt period in 2013 at the wet fen while it showed slightly positive values (4.3 W m^{-2}) at the dry heath (Fig. 4~~3a~~). The latent heat flux (LE) increased gradually up to about 18 W m^{-2} at the wet fen and up to 23 W m^{-2} at the dry heath (Fig. ~~3a~~4). During this initial period the net radiation increased gradually up to about 58 W m^{-2} at the wet fen and 43 W m^{-2} at the dry heath. Over the entire snow melt period, H dominated over LE at the dry heath (Bowen ratio 1.7) with mean daily average H and LE of 25.0 W m^{-2} and 14.9 W m^{-2}, respectively, while at the wet fen LE dominated over H (Bowen ratio 0.5), with average H and LE of 7.6 W m^{-2} and 15.6 W m^{-2} (~~Table 2~~Table 3). By the end of the snow melt period H accumulated 32.5 MJ m^{-2} at the dry heath and 3.5 MJ m^{-2} at the wet fen. The corresponding values for LE were 22.7 MJ m^{-2} and 21.1 MJ m^{-2}, respectively. This corresponds to accumulated evaporation of 9.3 mm and 8.6 mm of evaporated water during the entire spring snow melt at the dry heath and the wet fen.

During both years the ground heat flux (G) at the wet fen and the dry heath used ~10-15% of the total energy supplied by R_{net}. The prolonged snow melt period during the second year had no impact on the magnitude of G. However, the total amount of energy supplied to the ground was larger in 2014 than in 2013. At the dry heath, average G of 5.1 W m^{-2} in 2013 and 5.1 W m^{-2} in 2014 resulted in a total energy consumption of 8.0 MJ m^{-2} in the first year and 20.5 MJ m^{-2} in the second year. Similar behaviour was observed at the wet fen where average G of 8.4 W m^{-2} in 2013 and 7.2 W m^{-2} in 2014 added up to a total energy consumption of 10.2 MJ m^{-2} and 28.6 MJ m^{-2}. The average latent heat content of snow cover during the snow melt period in 2014 was 3.1 MJ m^{-2} which equals to 1.8% of R_{net} at the dry heath and 1.5% of R_{net} at the wet fen.

3.~~3~~ 4 Growing season

3.~~3~~4.1 Season length and meteorological conditions

The growing season in 2013 lasted 101 days at the wet fen (30 May – 8 September) and 100 days at the dry heath (31 May – 8 September). Compared to 2013, the season in 2014 was 30 days shorter on the wet fen (24 June – 4 September) and 31 days shorter at the dry heath (28 June – 4 September). The length of the growing season in the first year clearly exceeds the average 2000-2010 length (78 days) while the second year shows below-average length of the growing season (Lund et al., 2014). Mean July-August air temperatures (T_a) were similar in both years, reaching 6.5°C in the first year and 6.3°C in the second year, mean T_a over the entire growing seasons were lower in 2013 (5.3°C) compared to 2014 (6.1°C) (Fig. 5~~4~~). Growing season air temperature in 2013 was slightly below the 2000-2010 average (5.5°C) (Lund et al., 2014) and above-average in 2014. Total amount of precipitation during both years ~~reflect the dry summertime conditions~~clearly exceed the 2000-2010 average of 27.2 mm (Lund et al., 2014), reaching 80 mm in 2013 and 65.5 mm in 2014. In 2013, pronounced events of rainfall (>5 mm d^{-1}) occurred at the end of the growing season while in the second year precipitation mainly fell shortly after snow melt and in late-August (Fig. 5~~4~~).

~~in Zackenberg with 80 mm in 2013 and 65.5 mm in 2014. In the first year, pronounced events of rainfall (>5 mm d^{-1}) occurred at the end of the growing season while in the second year precipitation mainly fell shortly after snow melt and in late-August (Fig. 4).~~

3.~~3~~4.2 Radiation balance

During the growing season in 2013, mean daily R_{net} was slightly higher at the wet fen (114.2 W m^{-2}) compared to the dry heath (111.4 W m^{-2}) (~~Table 3~~Table 4) while during July-August both sites showed similar R_{net} (~93 W m^{-2}). Compared to 2013, mean daily R_{net} was slightly higher during July-August 2014, with 94.3 W m^{-2} at the wet fen and 98.6 W m^{-2} at the dry heath, but lower over the entire growing season, with 100.2 W m^{-2} and 98.9 W m^{-2}, respectively (~~Table 3~~Table 4, Fig. 6~~5~~). By the end of the season in 2013, accumulated R_{net} was 1006.6 MJ m^{-2} at the wet fen and 967.4 MJ m^{-2} at the dry heath compared to 632.2 MJ m^{-2} and 589.5 MJ m^{-2} in 2014. This increase of accumulated R_{net} by 59% (fen) and 64% (heath) in 2013 relates to the earlier onset of the growing season. By 24 June 2013, accumulated R_{net} at the wet fen reached 406 MJ m^{-2} during the first 25 days of the growing season while in 2014, the growing season started on 24 June and the surface was thus still snow covered until that date. Similar values were observed at the dry heath (423 MJ m^{-2}).

In 2013, mean surface albedo at both sites increased gradually during the growing season and reached its maximum towards the end of the season. Over the entire growing season albedo was higher at the wet fen (0.20) compared to the dry heath (0.16). During a snow fall event on 30 August 2013 albedo increased up to 0.32. Similar trends in albedo were observed in 2014 but mean surface albedo over the entire growing season was lower compared to 2013 with 0.17 at the wet fen and 0.13 at the dry heath. The ~~interannual~~ differences between the two years are more pronounced during the period July-August when mean albedo was 0.20 (2013) and 0.16 (2014) at the wet fen and 0.16 (2013) and 0.12 (2014) at the dry heath. The pronounced visible differences in greenness during the two growing seasons (Fig. 1b) was also reflected in average NDVI, with higher values observed in 2014 (0.49) compared to 2013 (0.45) (Table 4).

3.~~3~~4.3 Turbulent heat fluxes

The magnitude of the turbulent heat fluxes and the total amount of accumulated energy by *H* and *LE* revealed remarkable differences between the two years (Fig. 6~~5~~, Fig. 7~~6~~). Over the entire growing season in 2013, average fluxes of *H* and *LE* used 56% (62.6 W m^{-2}) and 14% (16.0 W m^{-2}), respectively, of R_{net} at the dry heath. The corresponding values for the wet fen were 37% (41.5 W m^{-2}) and 30% (25.2 W m^{-2}), respectively (~~Table 3~~Table 4). This clear dominance of *H* over *LE* at both locations is also reflected in the average Bowen ratio (*H/LE*) which reached a maximum of 3.9 at the dry heath and 1.6 at the wet fen. During 2014, *LE* at the dry heath used 26% (29.3 W m^{-2}) of R_{net} (~~Table 3~~Table 4). This corresponds to an almost doubling of *LE* compared to 2013. Mean fluxes of *H* at the dry heath were 36.6 W m^{-2} and *H* used 37% of R_{net}. Average Bowen ratio reached 1.3 which indicates a growing importance of *LE* at the dry heath compared to 2013. At the wet fen, mean daily *LE* was 23.3 W m^{-2} and *LE* used 25% of R_{net}. The corresponding value for *H* was 26.6 W m^{-2} and *H* used 29% of R_{net}. Average Bowen ratio reached 1.1.

From the first day after snow melt until the last day of the growing season in 2013 accumulated *H* was 546.2 MJ m^{-2} at the dry heath and 365.7 MJ m^{-2} at the wet fen while accumulated *LE* was 139.9 MJ m^{-2} and 222.0 MJ m^{-2}, respectively (Fig. 7~~6~~). By the end of the growing season in 2014, however, accumulated *H* was 220.2 MJ m^{-2} at the dry heath and 167.8 MJ m^{-2} at the wet fen. The corresponding values for *LE* were 174.7 MJ m^{-2} and 146.9 MJ m^{-2}, respectively (Fig. 7~~6~~). The observed values of accumulated *H* at the dry heath during 2014 correspond to a decrease in accumulated *H* by 60% and an increase in accumulated *LE* by 24% compared to 2013. At the wet fen, accumulated *H* and *LE* in 2014 correspond to a decrease by 44% and 33%, respectively, compared to 2013.

The total accumulated evapotranspiration (*ET*) differed significantly between the seasons (Fig. 8~~6~~). At the wet fen, total *ET* reached 91 mm during the growing season in 2013 and 48 mm in 2014. These values correspond to ~114% and ~73% of the total precipitation during the growing seasons within the corresponding years. However, total *ET* at the dry heath remained below the growing season precipitation during the first growing season (57 mm, ~71%) and exceeded precipitation in the second growing season (80 mm, ~122%).

3.~~3~~4.4 Controls of evapotranspiration

During both growing seasons, lower wind velocity at the dry heath compared to the wet fen resulted in slightly larger aerodynamic resistances (r_a) at the latter site. Daily average r_a showed no clear difference between the two years ranging between 75-82 s m^{-1} in both years at the wet fen. The corresponding values at the dry heath were between 107-120 s m^{-1} with slightly larger variability compared to the wet fen (~~Fig. 7~~Fig. 9). No significant changes during the course of both growing seasons indicate that r_a appeared to be independent of *RS*↓ and R_{net} and therefore ~~was~~ mainly ~~dependent on~~driven by atmospheric conditions.

The surface resistance (r_s) during both growing seasons, however, was characterized by large differences between the wet fen and the dry heath and high daily fluctuations at the latter site (~~Fig. 7~~Fig. 9). Daily average r_s at the dry heath ranged from 93 to 923 s m^{-1} in 2013 and from 64 to 428 s m^{-1} in 2014, with higher mean r_s in 2013 (556 s m^{-1}) compared to 2014 (247 s m^{-1}). During the first growing season r_s showed a general increase with increasing air temperature (T_a), ranging from ~455 s m^{-1} when T_a <0°C to ~804 s m^{-1} when T_a >12°C. During the second growing season r_s decreased from ~297 s m^{-1} when T_a <0°C to ~210 s m^{-1} when T_a was between 3-6°C, followed by a~~n~~ slight increase to 250 s m^{-1} when T_a >12°C. However, no such trend was observed at the wet fen and the surface resistance had no pronounced daily fluctuations with daily averages ranging between 53 and 455 s m^{-1}.

The McNaughton and Jarvis decoupling factor (Ω) expresses the degree of aerodynamic and radiative coupling between the vegetation and the atmosphere. The wet fen and the dry heath were characterized by mean daily Ω below or close to 0.5 during both growing seasons which indicates a relatively high contribution of vapour pressure deficit (*VPD*) on the control of *ET* (~~Table 3~~Table 4, ~~Fig. 7~~Fig. 9). However, mean daily Ω during the first growing season was lower at the dry heath (0.30) compared to the wet fen (0.38) but showed a reverse trend during the second year with 0.52 compared to 0.48. The general decrease in Ω over the course of the first season at the dry heath terminated around mid-August and Ω started to increase for the rest of the season. Similar behaviour for Ω was observed at the wet fen where Ω started to increase around late-August. The second growing season showed a general decrease in Ω at both sites. During both growing seasons Ω gradually decreased as r_s increased. The Priestley-Taylor coefficient (α) showed large day-to-day variations, particularly at the wet fen, ranging between 0.05 and 1.06 in 2013 and 0.21 and 1.13 in 2014. The seasonal mean of α was 0.60 and 0.69 with a standard ~~deviation~~ error of 0.02~~21~~ and 0.03~~22~~ for the respective seasons. The day-to-day variation was less pronounced at the dry heath with seasonal means of 0.44 and 0.74 and standard ~~variations~~ error of 0.02~~18 and 0.17~~ for both years. (~~Table 3~~Table 4, ~~Fig. 7~~Fig. 9).

3.~~3~~4.5 Ground heat flux and soil properties

The ground heat flux (*G*) was the smallest flux in both ecosystems but due to the strong heat sink of permafrost *G* is a vital component of the surface energy budget in this high-latitude environment. The differences in snow cover between the two years caused distinct differences in the soil water content during the two growing seasons, with strong impact on the partitioning of R_{net} into *G* at the dry heath. Average soil moisture content at the dry heath of 19% in 2013 and 34% in 2014 restrained thermal conductivity more during 2013 than during 2014. Consequently, only 5% of R_{net} (5.6 W m^{-2}) was partitioned into *G* in 2013 while during 2014 *G* used 10% of R_{net} (10.1 W m^{-2}). At the wet fen, mean daily *G* used 12% of R_{net} (10.8 W m^{-2}) in 2013 while in 2014, *G* used 17% of R_{net} (15.2 W m^{-2}).

During the course of the two growing seasons *G* reached its maximum shortly after snow melt due to the strong thermal gradient between the soil surface and the underlying permafrost (Fig. 6~~5~~). However, the low soil moisture content at the dry heath during the first growing season weakened the *G* signal after the snow melt. No clear seasonal trend in the development of *G* to R_{net} was observed for both growing seasons and locations. By the end of the first growing season accumulated *G* was

48.7 MJ m^{-2} at the dry heath and 94.7 MJ m^{-2} at the wet fen (Fig. 7~~6~~). Increased thermal conductivity due to higher soil moisture content in 2014 compared to 2013 amplified the total amount of accumulated *G* at the dry heath in the latter year although prolonged snow cover reduced the length of the second growing season. By the end of the second growing season accumulated *G* was 60.1 MJ m^{-2} at the dry heath (+23% compared to 2013) while at the wet fen, no clear difference in accumulated *G* was observed (95.6 MJ m^{-2}).

3.~~4~~ 5 Total surface energy balance of the snow melt season and growing season

From the first day of the beginning of the snow melt period until the last day of the growing season in 2013 R_{net} accumulated 1043.5 MJ m^{-2} at the dry heath and 1100.9 MJ m^{-2} at the wet fen. The corresponding values for 2014 were 764.0 MJ m^{-2} and 835.1 MJ m^{-2}, respectively. Accumulated ground heat flux for the same time period was 56.7 MJ m^{-2} at the dry heath and 103.8 MJ m^{-2} at the wet fen in 2013 and 83.2 MJ m^{-2} and 125.3 MJ m^{-2} in 2014, respectively. These values correspond to a total amount of accumulated available energy at the surface ($R_{net} – G$) of 986.8 MJ m^{-2} at the dry heath and 997.1 MJ m^{-2} at the wet fen in 2013. In 2014, $R_{net} – G$ was 683.4 MJ m^{-2} at the dry heath and 711.8 MJ m^{-2} at the wet fen which, compared to 2013, relates to a decrease in available energy at the surface by -31% and -29%, respectively.

In 2013, the amount of total *H* loss was 578.7 MJ m^{-2} at the dry heath and 369.2 MJ m^{-2} at the wet fen while total *LE* loss was 162.6 MJ m^{-2} and 243.1 MJ m^{-2}, respectively. These values add up to a total energy consumption of *H* and *LE* (*H*+*LE*) of 741.3 MJ m^{-2} at the dry heath and 612.3 MJ m^{-2} at the wet fen.

~~3.5 Energy balance closure~~

~~The observed slopes of the regressions between available energy at the surface ($R_{net} – G$) and the sum of the turbulent heat fluxes (*H*+*LE*) serve as an indicator for the energy balance closure. Figure 8 shows the comparison between mean daily $R_{net} –$ *G* and mean daily *H*+*LE* for the two study sites. The observed slopes at the wet fen are 0.68 during both 2013 and 2014. For the dry heath the slopes are 0.81 (2013) and 0.82 (2014).~~

4 Discussion

4.1~~2~~ Energy balance closure and system performance

The observed values of energy balance closure lie in the range of other energy balance closure terms reported from various field studies in Arctic environments (Westerman et al., 2009; Langer et al., 2011; Liljedahl et al., 2011) and are in good agreement with earlier long-term observations from the dry heath (Lund et al., 2014). Studies on the closure problem of eddy covariance measurements highlight the landscape heterogeneity as a driving factor for the lack of closure (Stoy et al., 2013) but also stress the importance of measurement scales (Foken, 2008). Due to the striking small-scale heterogeneity of soil moisture availability~~-~~ and vegetation cover in Arctic landscapes, measurements of point-scale *G* and radiative components may not represent the large source area of eddy covariance *H* and *LE*. However, at our sites a flux footprint analysis at the dry heath revealed that fluxes of *H* and *LE* on average originate from the *Cassiope* heath (Lund et al., 2012) while the highest contribution of fluxes at the wet fen originates from the continuous fen area (Tagesson et al., 2012). Large variability in soil heat capacity due to spatial variation in soil moisture may account for underrepresentation of the stored energy between the heat flux plates and the soil surface within the eddy covariance flux footprint area (Leuning et al., 2012). Additional uncertainty in the assessment of *G* arises from small-scale variation in active layer depth and soil thermal gradients.~~.~~

Previous studies have shown large high-frequency flux attenuation of traditional closed-path gas analysers (Haslwanter et al., 2009), such as used in this study at the dry heath site, caused by tube walls and tube age (Su et al., 2004; Massman and Ibrom, 2008) and tube length (Novik et al., 2013). Enclosed-path systems, however, reduce flux attenuation compared to traditional closed-path systems due to shorter tube length (Burba et al., 2010; Novick et al., 2013). Sample screening of cospectra at our two study sites (data not shown) showed that frequency losses for water vapour and sensible heat flux were more pronounced at the wet fen (enclosed-path system) compared to the dry heath (closed-path system). At both locations, the attenuation is generally greater for water vapour flux than for sensible heat flux and at higher frequencies ($n > 0.1$), normalized cospectra for water vapour flux was lower at the wet fen compared to the dry heath. Interannual comparison of cospectra for both wet fen and dry heath showed similar behaviour of water vapour and sensible heat flux. Thus, we conclude that besides the heterogeneity of the tundra surfaces, high-frequency losses of both water vapour and sensible heat fluxes contribute to the observed surface energy imbalance. However, since surface energy imbalance is consistent over the two study years we are confident that the measured surface energy balance components are adequately represented for the purpose of this study.

4.2~~1~~ Snow cover and surface energy budget

The disappearance of the snow cover and the onset of the growing season coincide with the time period when incoming solar radiation ($RS\downarrow$) is at its annual peak and the surface (soil or snow) receives high irradiance from $RS\downarrow$. During the snow melt period most of R_{net} is used for warming and melting of the snow pack and therefore not available for atmospheric warming through sensible heat fluxes. This pattern was reflected in the average air temperature of the two snow melt periods which showed only small differences between 2013 and 2014 although the snow melt period in 2014 was much longer compared to 2013. The combination of snow layer thickness, snow physical properties such as density or grain size (Warren, 1982), ~~and~~ the fraction of exposed dark underlying surface and type of vegetation (Sturm and Douglas, 2005) control the snow and soil surface albedo, with direct impact on R_{net}. Our results showed that low and partly absent snow cover in the winter 2012/13 resulted in a short snow melt period dominated by low albedo of the snow-soil surface and increased average R_{net}. Simultaneously, sensible heat fluxes dominated at the dry heath while latent heat fluxes dominated at the wet fen. Relatively thick snow cover and a prolonged snow melt period in 2014 increased surface albedo and limited average R_{net}. Further, the total energy accumulated by R_{net} during the snow melt period was higher in 2014 compared to 2013.

During the snow melt period, only a small fraction of R_{net} can be used by plants for growth and development as the snow ~~shields off~~reflects most of the incoming solar radiation and sustains relatively low surface temperatures (Walker et al., 2001). Consequently, a prolonged period of snow cover and snow melt at our study sites in 2014 delayed the onset of the growing season and limited the amount of total R_{net} available for plant metabolism. In coherence with that, the magnitude of the surface energy balance components and the partitioning of R_{net} into *H*, *LE* and *G* continued to be influenced by the presence of the snow. An earlier disappearance of the snow in 2013, however, was related to an earlier increase in the magnitude of R_{net} at the surface which facilitated earlier plant development and growth, soil warming and permafrost active layer development through *G*, evapotranspirative heat loss through *LE*, and atmospheric warming through *H*.

The disappearance of the snow and related increase in surface heating mark the transition into a convective summer-type precipitation regime (Callaghan et al., 2011b) which initiates a rapid and distinct change in both plant metabolism and surface energy balance. Ongoing and predicted climate change, however, promotes an increase in atmospheric moisture, winter snowfall over land areas (Rawlins et al., 2010), and ~~interannual~~ variability in the amount of snowfall (Callaghan et al., 2005; Kattsov et al., 2005; Stocker et al., 2013) while higher temperatures stimulate an earlier snow melt and transition to convective precipitation patterns (Groisman et al., 1994). We observed that the impact of this ~~interannual~~ variability in snow cover and snow melt on the seasonal surface energy budget is strongly connected to the storage of meltwater in the soil and its evaporation and transpiration over the subsequent growing season. A higher proportion of soil moisture, combined with a high atmospheric moisture demand, generally stimulates *ET*. In our study, the impact of the availability of soil moisture from snow melt and its loss through *ET* on the surface energy budget was most pronounced at the heath. Here we observed that low soil moisture content and lack of summertime precipitation in 2013 amplified *H* at the cost of *LE* and *G* while increased soil moisture in 2014 and a pronounced rainfall event in the middle of the growing season favoured *LE* and *G* at the cost of *H*. Further, the Bowen ratio of the heath during the same year showed that energy partitioning into *H* and *LE* was similar to the wet fen. In contrast, the wet fen showed attenuated behaviour of *LE*, *ET*, *H* and *G* to the variability in snow meltwater as the fen receives its moisture supply mostly from ~~groundwater close to the surface~~minerotrophic water supply which remained relatively stable over the two study years. Growing season variability in the partitioning of the surface energy balance components was also observed at a polygonal tundra site in Siberia (Boike et al., 2008). However, the observed differences were mainly driven by variability in summertime precipitation.

Negative water balances during the growing season, with *ET* exceeding precipitation, are common in high-latitude ecosystems (Woo et al., 1992). Depending on the type of water supply, tundra ecosystems may therefore experience differential responses to climate variability and climate change (Rouse, 2000; Boike et al., 2008). At the wet fen, our observations showed negative water balances during the growing season 2013 but the loss of water through *ET* was compensated by moisture supply from ~~groundwater~~soil moisture. Consequently, the partitioning of R_{net} into *LE* showed only small differences between the two growing seasons. At the dry heath, the growing season in 2013 ended with a positive water balance. However, this was related to both pronounced precipitation at the end of the season and to low rates of *ET* due to declining R_{net}. During most of the season snow meltwater was the only supplier of soil moisture and the small amount of snow meltwater was evaporated relatively soon after snow melt. Consequently, for most parts of the remaining season the soil was not able to supply moisture for *ET*. This resulted in low *LE*, relatively low soil thermal conductivity and *G*, and in a clear dominance of *H*. During the growing season in 2014, the water balance of the heath was negative over the entire season but the soil experienced greater saturation from snow meltwater storage which was reflected in the partitioning of the surface energy balance towards a greater share of *LE* and *G* on R_{net}.

The effects of *VPD*, soil moisture and air temperature on plant stomata and the impact of r_s on *ET* and *LE* has been documented for a large number of species and ecosystems (Losch and Tenhunen, 1983; Lafleur and Rouse, 1988; Kasurinen et al., 2014). At the dry heath, the observed values of r_s suggest strong vegetation response to the different regimes of snow and surface wetness in the two study years compared to previous studies (Soegaard et al. 2001; Lund et al., 2014), while at the wet fen attenuated behaviour of r_s was observed. Arctic ecosystems are generally characterised by a high proportion of free water and mosses which, unlike vascular plants, limit moisture transfer during high *VPD*. However, the concept of surface resistance neglects this contribution of free water and non-vascular plants (Kasurinen et al., 2014) and therefore the application of r_s and Ω is difficult in Arctic environments. The seasonal differences in r_s at the dry heath may also be explained by the characteristics of the growing season precipitation regimes and water content of the moss-soil layer (McFadden et al., 2003). Bowen ratio, r_s and Ω were closely-coupled to precipitation, resulting in a decrease in Bowen ratio, r_s and Ω during periods of rainfall while longer periods without precipitation resulted in high values of Bowen ratio, r_s and Ω. This behaviour for all parameters was more pronounced in 2013 compared to 2014. In 2013, the combined effects of low soil moisture, lack of precipitation during the period with relatively high $RS\downarrow$ and high *VPD* may be responsible for the observed magnitudes.

V~~Interannual v~~ariability of snow cover and length of the growing season is not only reflected in the partitioning of the surface energy balance components. More important, total accumulated R_{net} increases with increased length of the snow-free period. Further, any increase in the length of the snow-free season or in summer temperatures is manifested in a general increase in *ET*, resulting in negative water balances over the snow-free season if precipitation shows no increase (Eugster et al., 2000). Our results showed that with the onset of the snow melt period and growing season during the part of the year when incoming solar radiation is at its peak, an earlier onset of the growing season of approx. four weeks resulted in dramatic differences in accumulated energy fluxes at the end of the growing season. Summarizing, the increased amount of accumulated R_{net} contributed to increased *ET* and surficial heat loss from *LE*, soil and permafrost warming through *G*, and atmospheric warming through *H*.

~~4.2 Energy balance closure and system performance~~

~~The observed values of energy balance closure lie in the range of other energy balance closure terms reported from various field studies in Arctic environments (Westerman et al., 2009; Langer et al., 2011; Liljedahl et al., 2011) and are in good~~

~~agreement with earlier long-term observations from the dry heath (Lund et al., 2014). Studies on the closure problem of eddy covariance measurements highlight the landscape heterogeneity as a driving factor for the lack of closure (Stoy et al., 2013) but also stress the importance of measurement scales (Foken, 2008). Due to the striking small-scale heterogeneity of soil moisture availability and vegetation cover in Arctic landscapes, measurements of point-scale *G* and radiative components may not represent the large source area of eddy covariance *H* and *LE*. However, at our sites a flux footprint analysis at the dry heath revealed that fluxes of *H* and *LE* on average originate from the *Cassiope* heath (Lund et al., 2012) while the highest contribution of fluxes at the wet fen originates from the continuous fen area (Tagesson et al., 2012). Large variability in soil heat capacity due to spatial variation in soil moisture may account for underrepresentation of the stored energy between the heat flux plates and the soil surface within the eddy covariance flux footprint area (Leuning et al., 2012).~~

5 Conclusions and outlook

In this study we documented the effects of ~~interannual~~ variability in snow accumulation on the surface energy balance of a high-Arctic tundra ecosystem in Northeast Greenland during two subsequent years (2013-2014). The most important findings include:

- Low snow cover during the winter 2012/13 promoted low surface albedo and positive daily average R_{net} over the snow melt period in 2013 while extensive snow cover during the winter 2013/14 resulted in high albedo and reduced R_{net} during the snow melt period in 2014.
- The heath's energy budget was strongly affected by the variability in snow cover, resulting in substantial heat loss by *H* at the cost of *LE* and *G* in 2013 while in 2014, *LE* and *G* showed a strong increase at the cost of *H*. In contrast, the wet fen showed attenuated response to the ~~interannual~~ variability in snow cover due to differences in the local hydrological settings.
- At both sites, the variation in the length of the snow melt periods and growing seasons was manifested in substantial differences in the total amount of accumulated energy balance components.

Among the research community, mean values of the climatic site conditions, surface energy and carbon exchange have been regarded as powerful indicators for ecosystem productivity and model evaluation is widely based on these parameters. However, the frequency and magnitude of weather extremes and the pace of ongoing climate change are major challenges for ecosystems all over the planet. In the Arctic and subarctic, the closely-coupled hydrological, biological and soil thermal regimes respond nonlinearly to a myriad of controlling factors (Liljedahl et al., 2011). It is therefore essential to further incorporate such data of weather extremes into research and modelling tools (Jentsch et al., 2007), especially in the Arctic and subarctic, where the lack of observational studies result in a blur picture of high-latitude ecosystem response and contribution to climate change. The results of this study may be a valuable contribution for modelling tools as it is, to our knowledge, the first study that evaluates the impact of successive snow cover variability on the land-atmosphere interactions and surface energy balance components in Greenlandic tundra ecosystems.

Author contribution

The original idea for the paper was suggested by C.S., M.L. and A.L. and discussed~~s~~ and developed by all authors. M.L. and C.S. performed the data analysis. C.S. prepared the manuscript with contributions from all co-authors.

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Figures

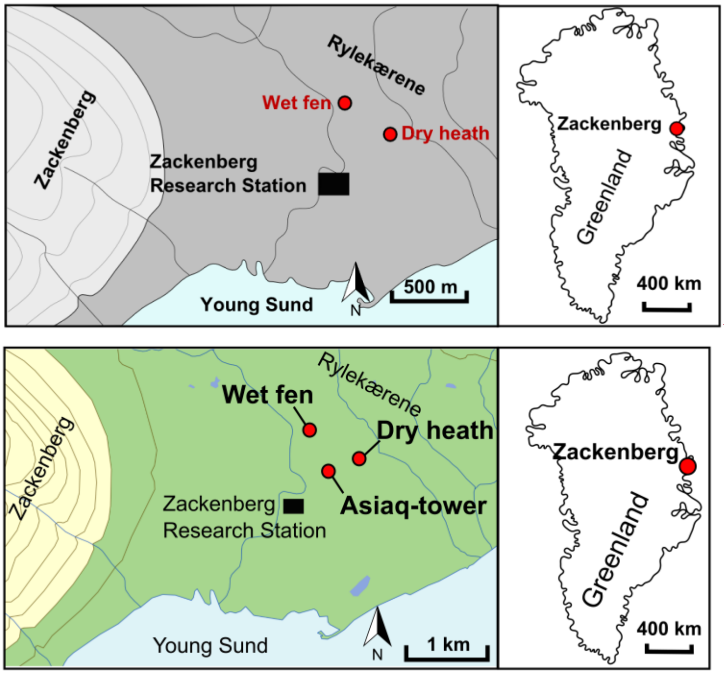


Figure 1a: Study location.

Location of the study sites in Zackenberg, Northeast Greenland (base map provided by NunaGIS).

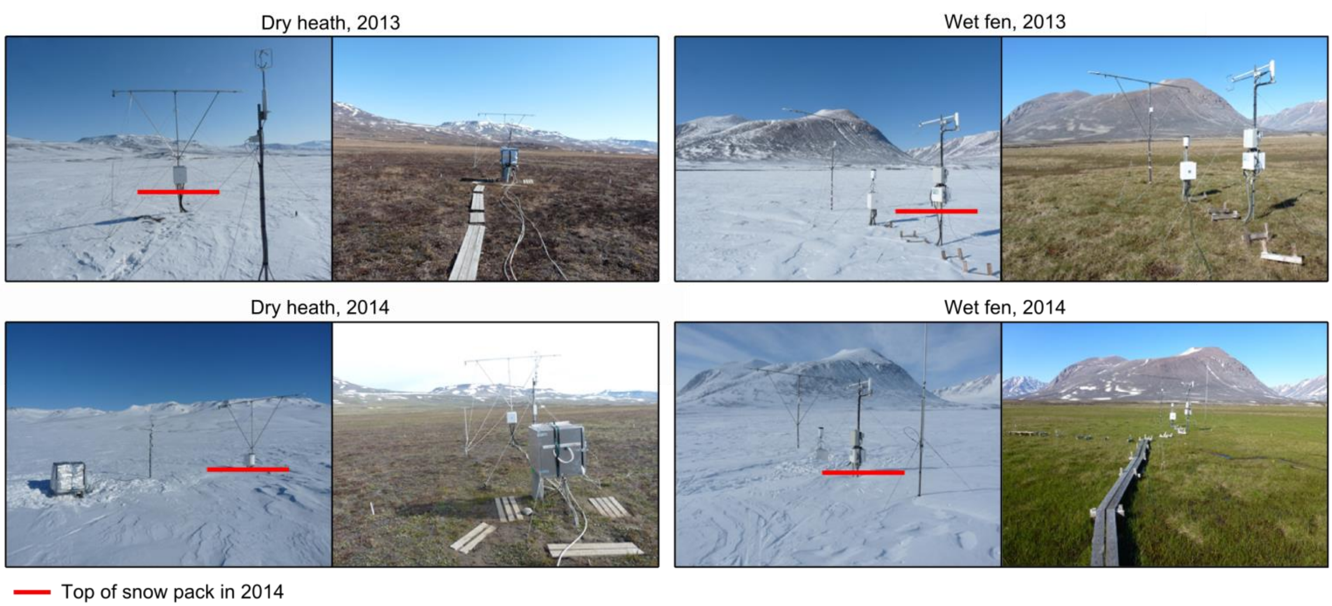


Figure 1b: Characteristics of the study sites.

Characteristics of the study sites during the beginning of the snow melt periods and during the growing seasons in 2013 and 2014.

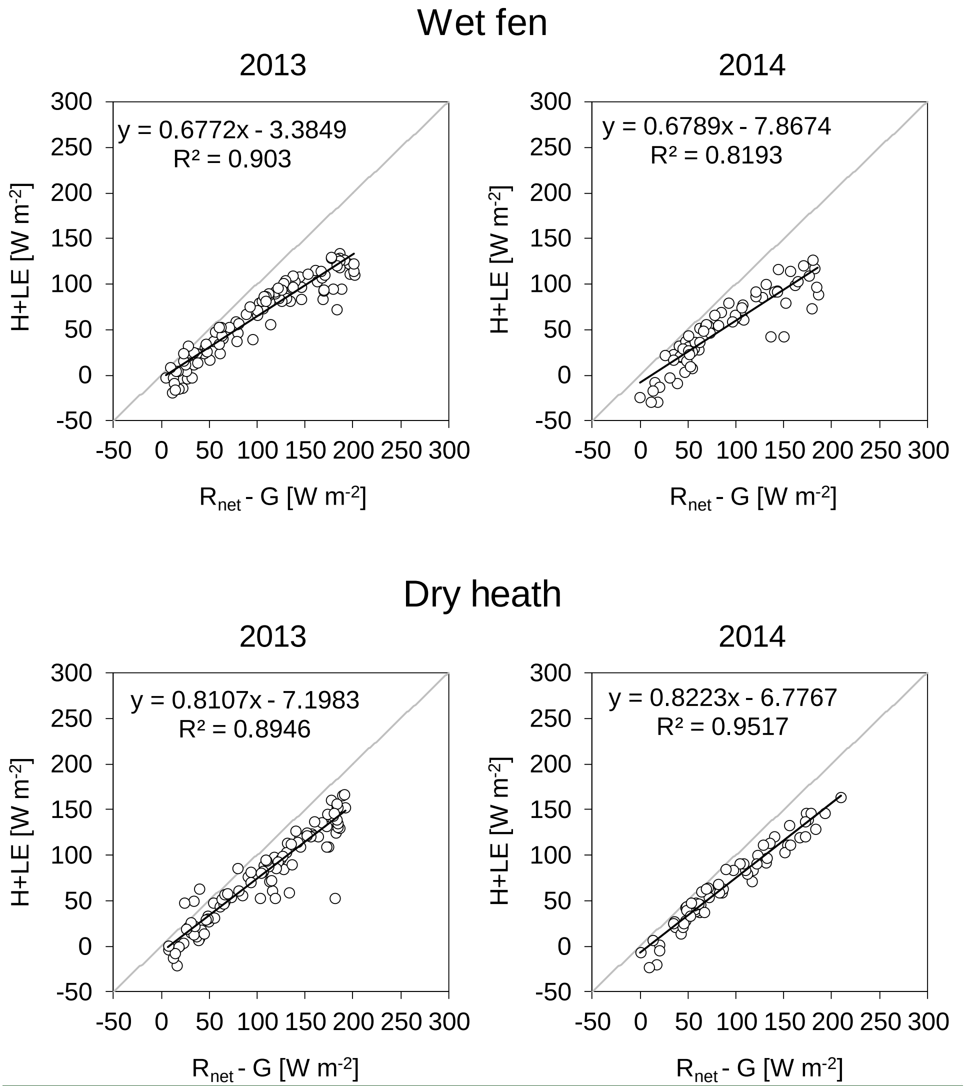
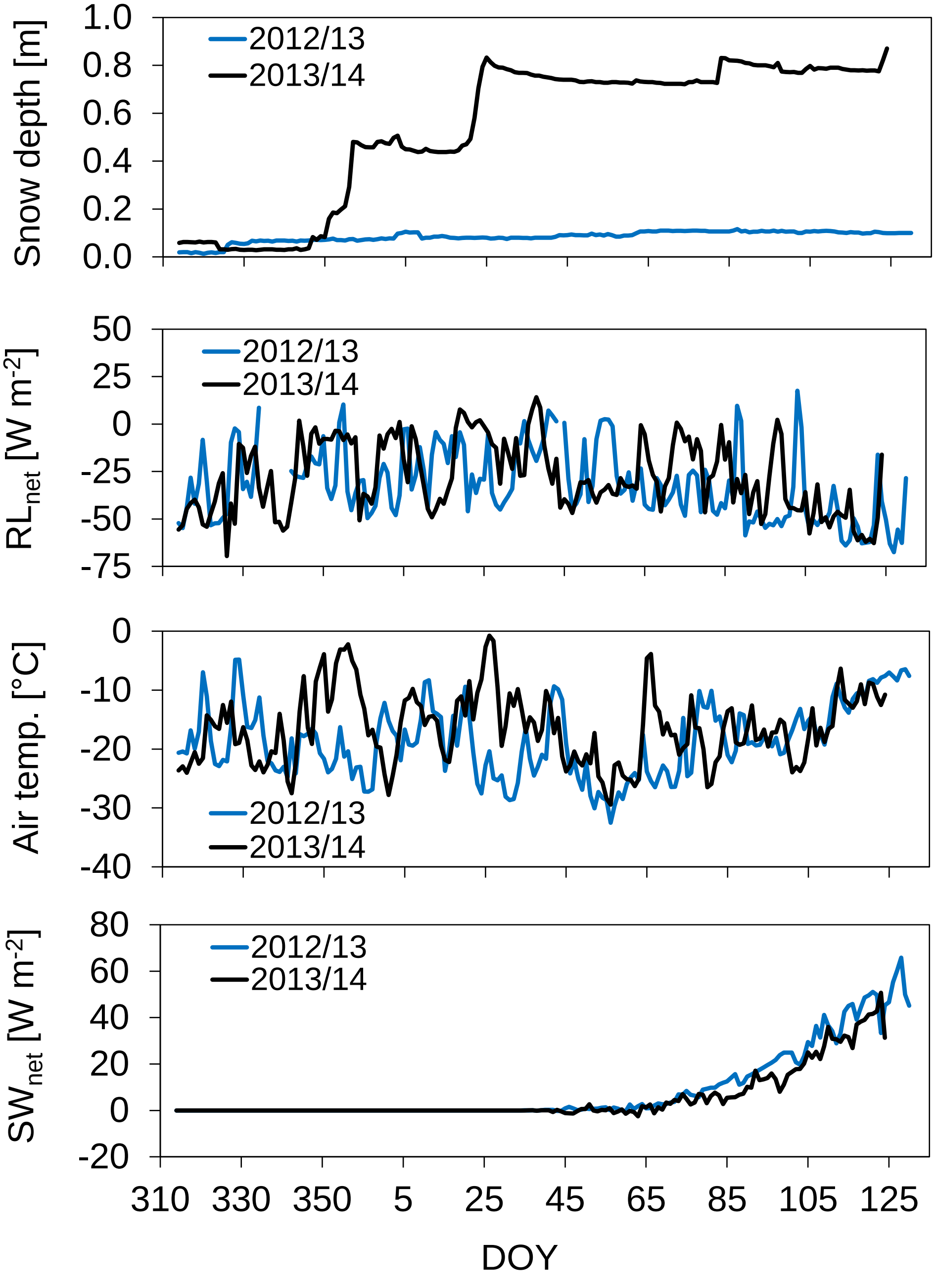


Figure 2~~8~~: Energy balance closure.

Mean daily available energy ($R_{net} – G$) and turbulent heat fluxes ($H+LE$) at the wet fen (upper) and the dry heath (lower) during the observation periods in 2013 and 2014.



Snow depth [m]
1.0
0.8
0.6
0.4
0.2
0.0
2012/13
2013/14
RL$_{net}$ [W m^{-2}]
50
25
0
-25
-50
-75
2012/13
2013/14
Air temp. [°C]
0
-10
-20
-30
-40
2012/13
2013/14
SW$_{net}$ [W m^{-2}]
80
60
40
20
0
-20
2012/13
2013/14
310
330
350
5
25
45
65
85
105
125
DOY

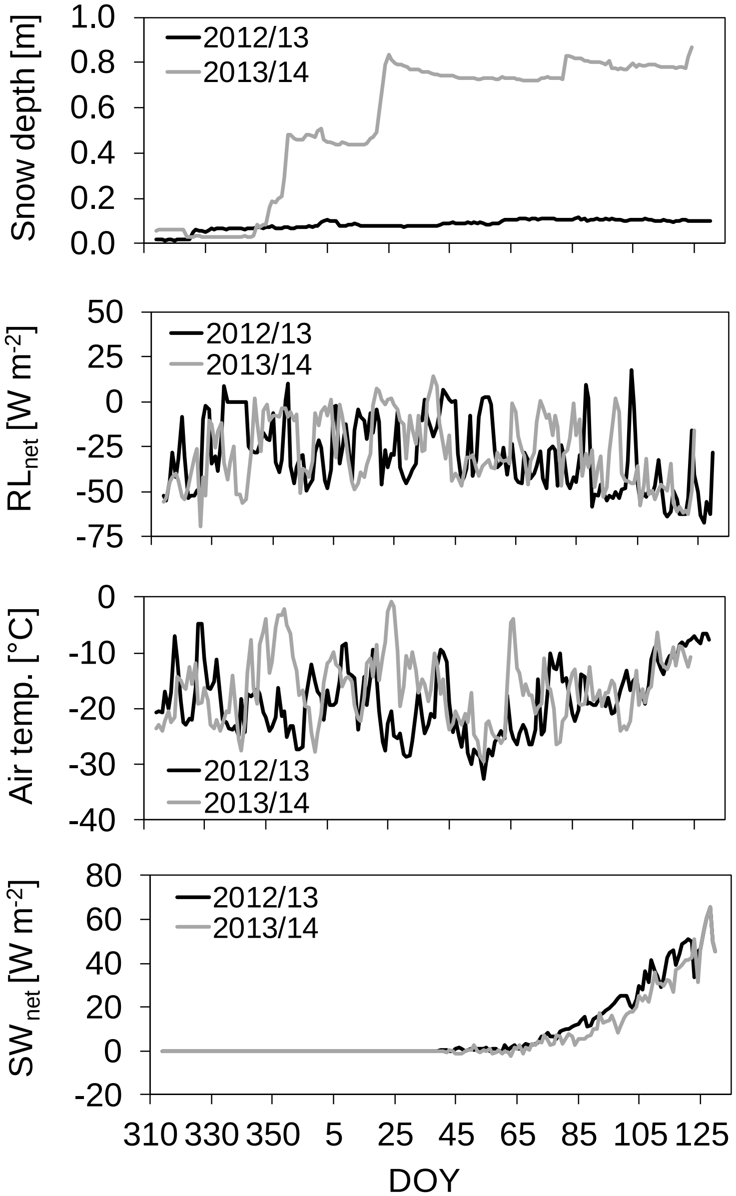
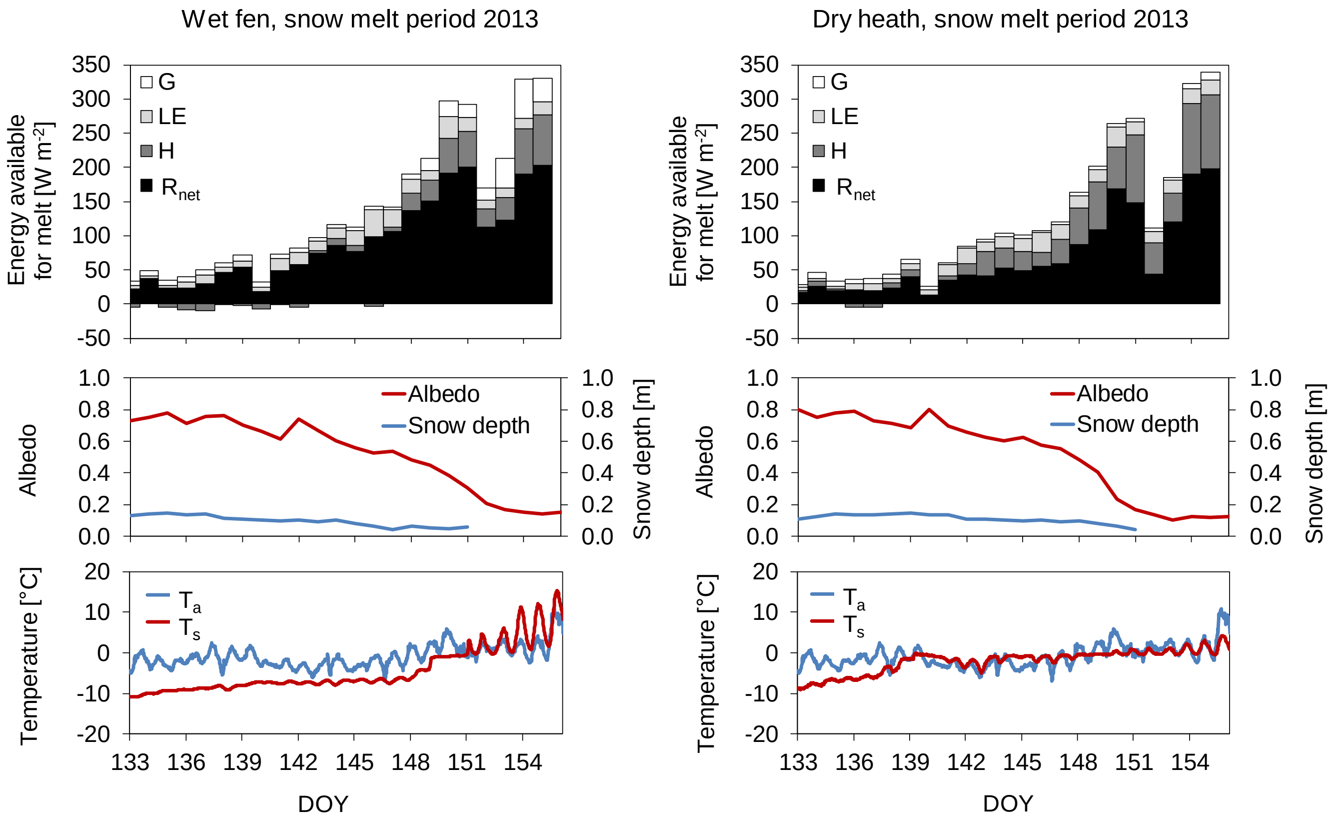


Figure ~~2~~3: Polar night and pre-melt seasons of the winters 2012/13 and 2013/14.

Characteristics of snow cover development, air temperature, net longwave radiation (RL_{net}) and net shortwave radiation (SW_{net}) during the polar night periods and subsequent pre-melt seasons of the winters 2012/13 and 2013/14 (Asiaq-station).


Wet fen, snow melt period 2013
Dry heath, snow melt period 2013
Energy available for melt [W m-2]
G
LE
H
Rnet
Albedo
Snow depth
Snow depth [m]
Temperature [°C]
Ta
Ts
DOY
133
136
139
142
145
148
151
154

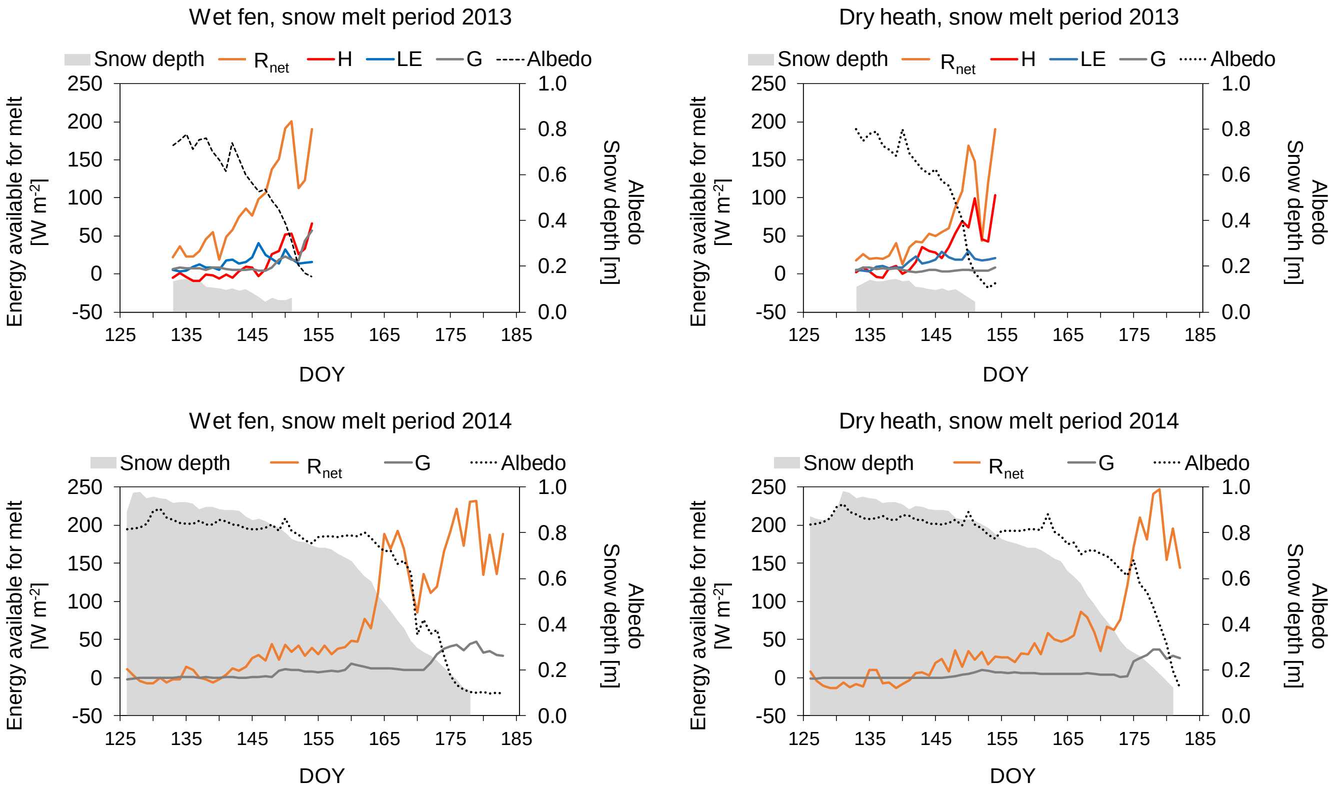
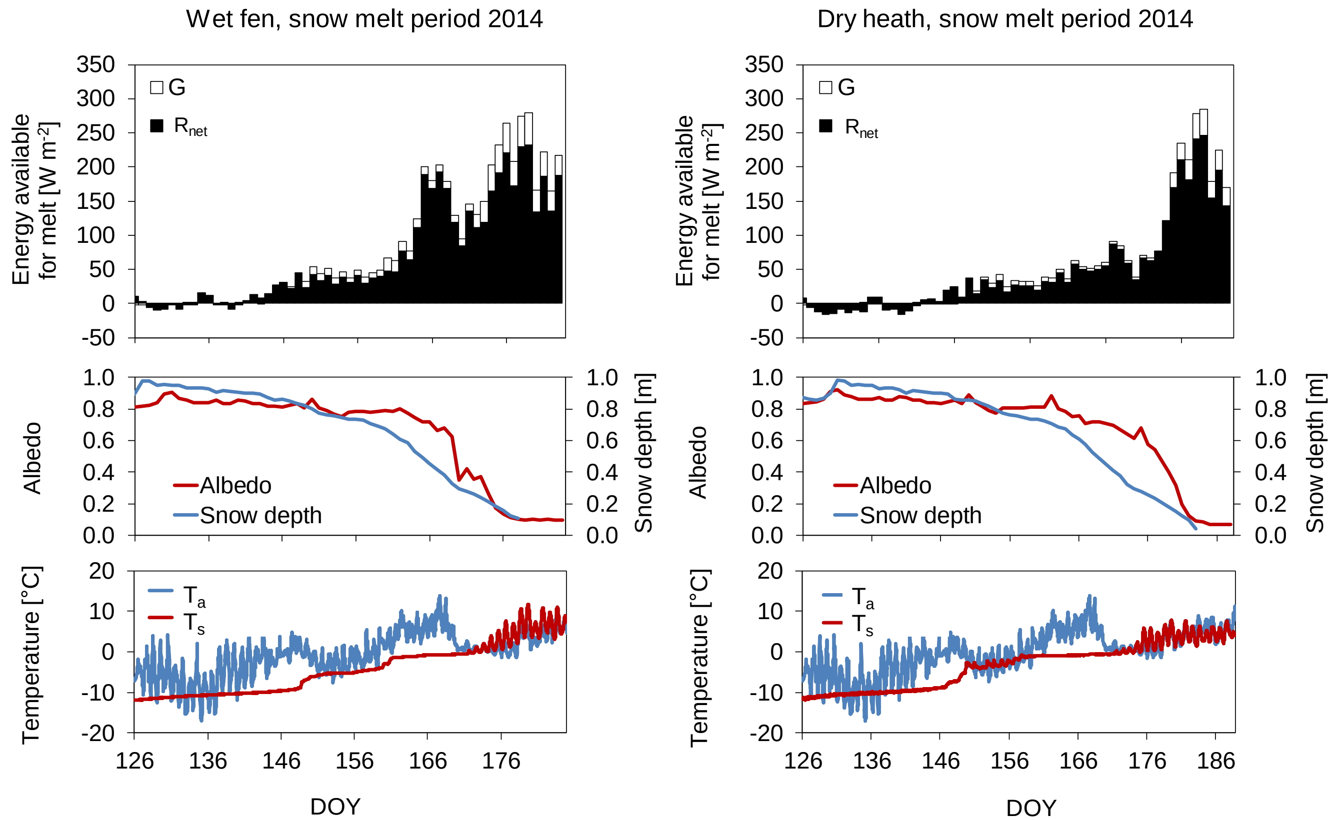


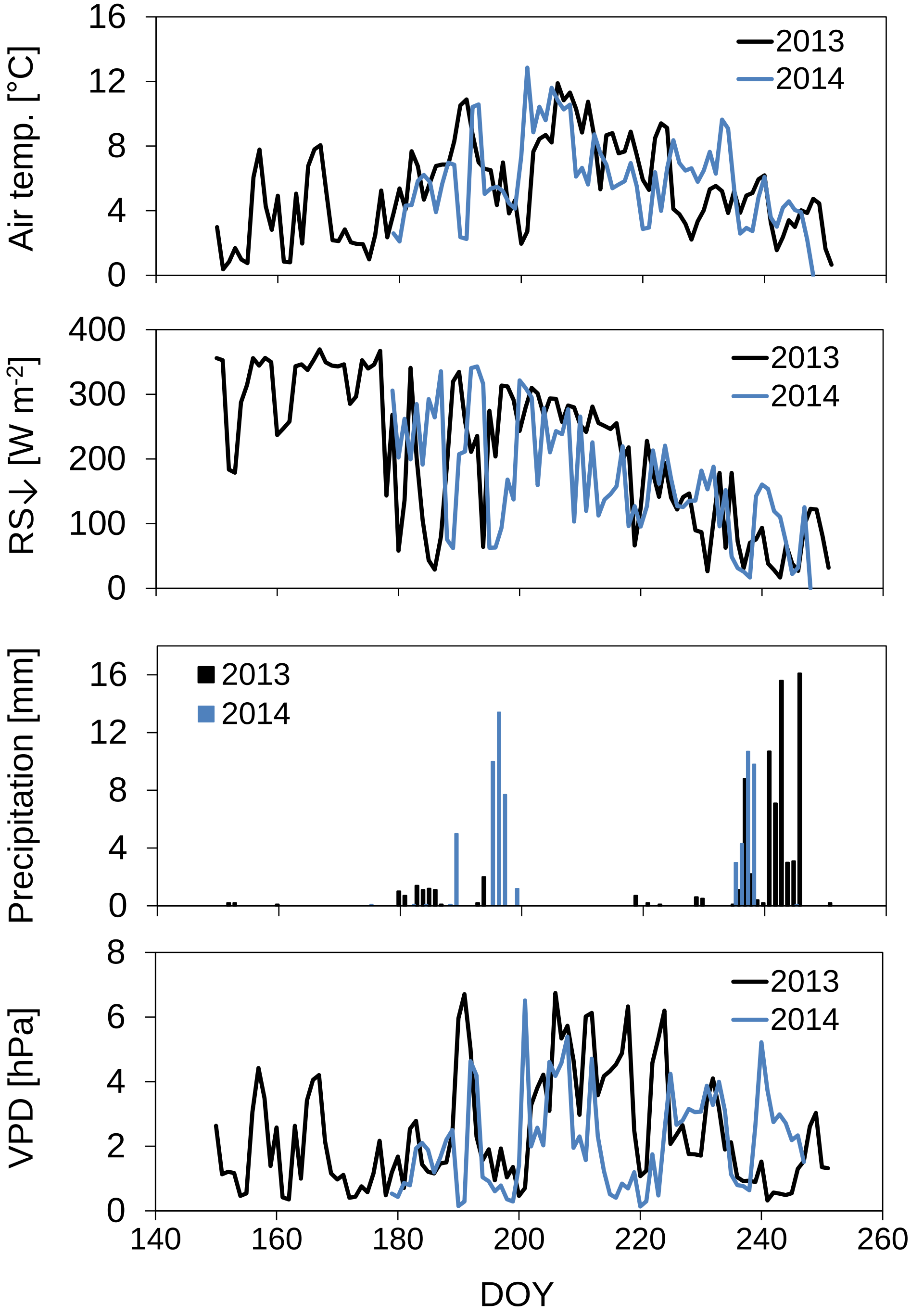
Figure ~~3a~~4: Snow melt periods 2013 and 2014.

Development of mean daily snow cover thickness, albedo, net radiation (R_{net}), sensible heat fluxes (H), latent heat fluxes (LE) and ~~,~~ ground heat fluxes (G)~~, air temperature (T_a), and soil temperature at 2 cm depth (T_s)~~ at the wet fen (left) and dry heath (right) during the snow melt period in 2013 and 2014 and first 5 days of the growing season in 2013 and 2014.



~~**Figure 3b:** Snow melt period 2014.~~

~~Development of mean daily snow cover thickness, albedo, net radiation (R_{net}), sensible heat fluxes (H), latent heat fluxes (LE), ground heat fluxes (G), air temperature (T_a), and soil temperature at 2 cm depth (T_s) at the wet fen (left) and dry heath (right) during the snow melt period in 2014 and first 5 days of the growing season in 2014.~~


16
12
8
4
0
Air temp. [°C]
2013
2014
400
300
200
100
0
RS↓ [W m-2]
2013
2014
16
12
8
4
0
Precipitation [mm]
2013
2014
8
6
4
2
0
VPD [hPa]
2013
2014
140
160
180
200
220
240
260
DOY

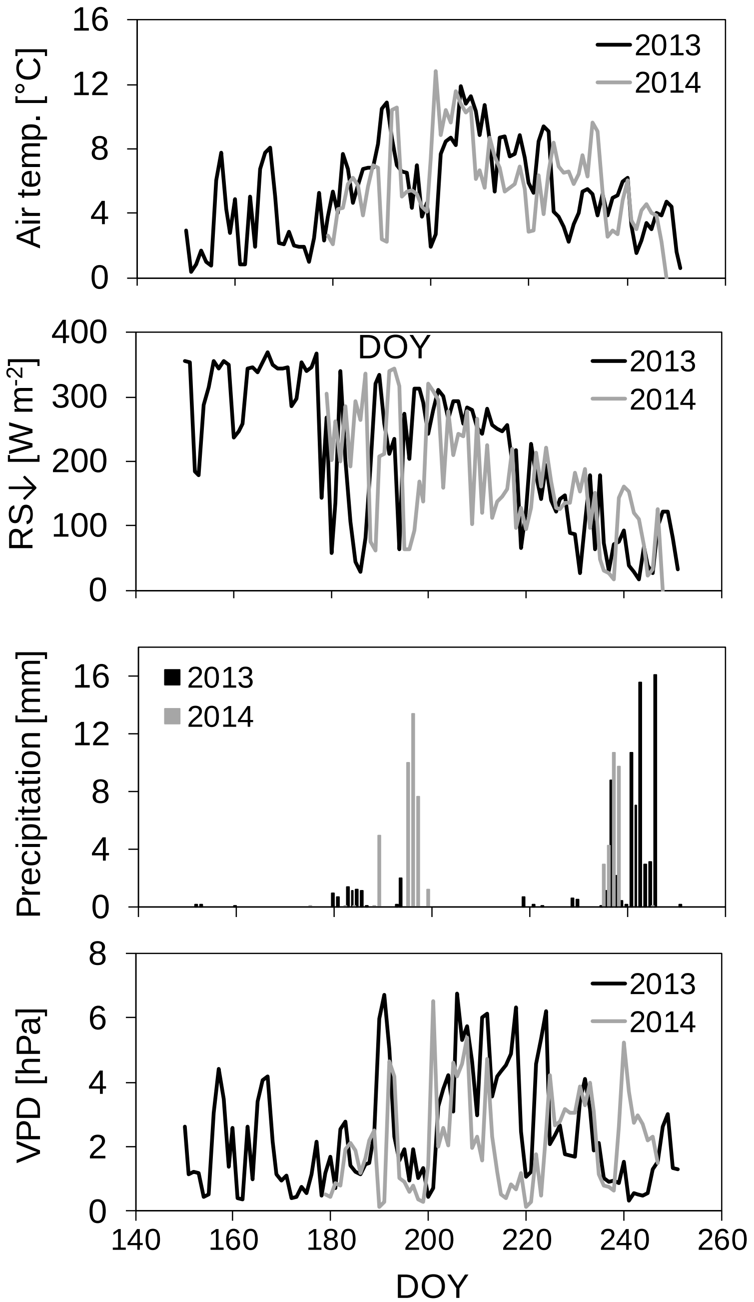


Figure 45: Growing seasons 2013 and 2014.

Development of mean daily air temperature, precipitation, incoming solar radiation (*RS*↓) and vapour pressure deficit (*VPD*) during the growing seasons in 2013 and 2014 (Asiaq-station).

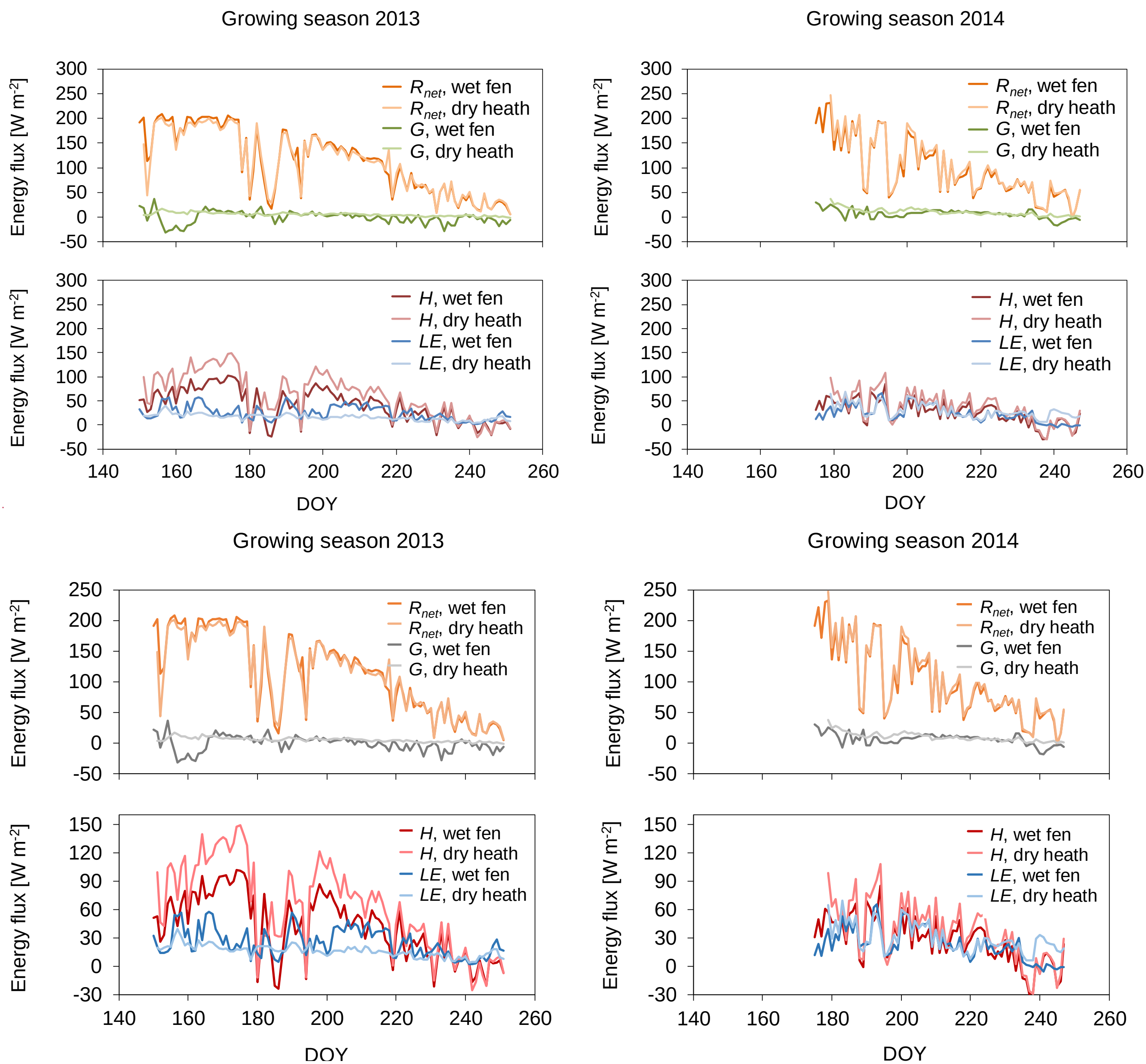
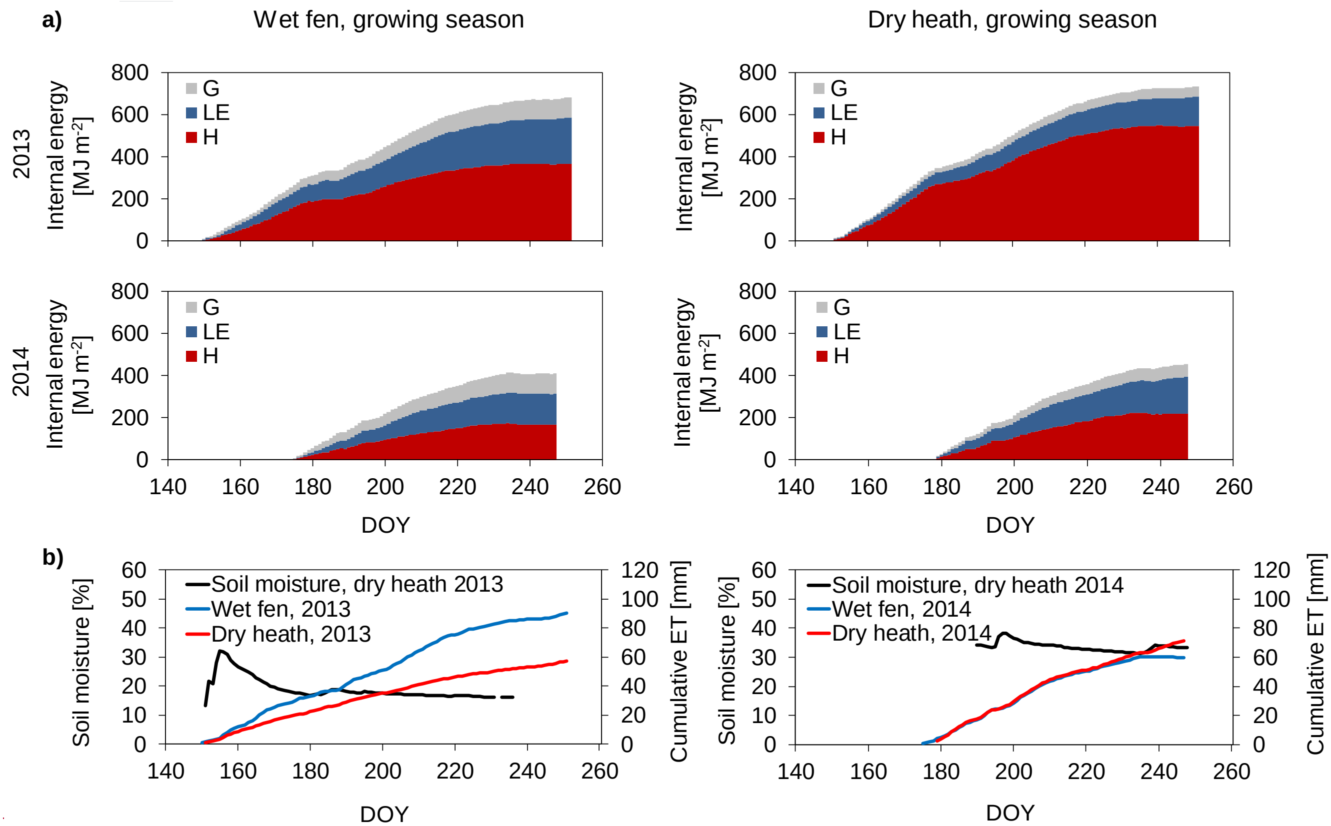


Figure ~~5~~6: Growing season energy fluxes.

Mean daily net radiation (R_{net}), sensible heat flux (H), latent heat flux (LE) and ground heat flux (G) at the wet fen and dry heath during the growing seasons in 2013 (left) and 2014 (right).



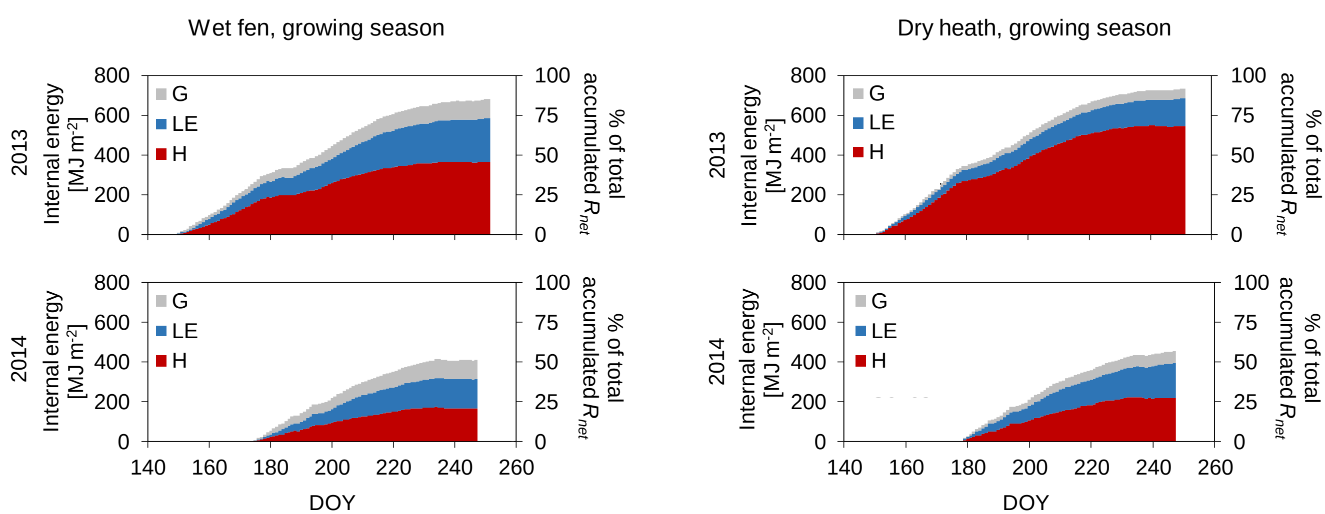


Figure ~~6a~~7: Development of internal energy.

Accumulated ground heat (G), latent heat (LE) and sensible heat (H) at the wet fen (left) and the dry heath (right) during the growing seasons in 2013 and 2014.

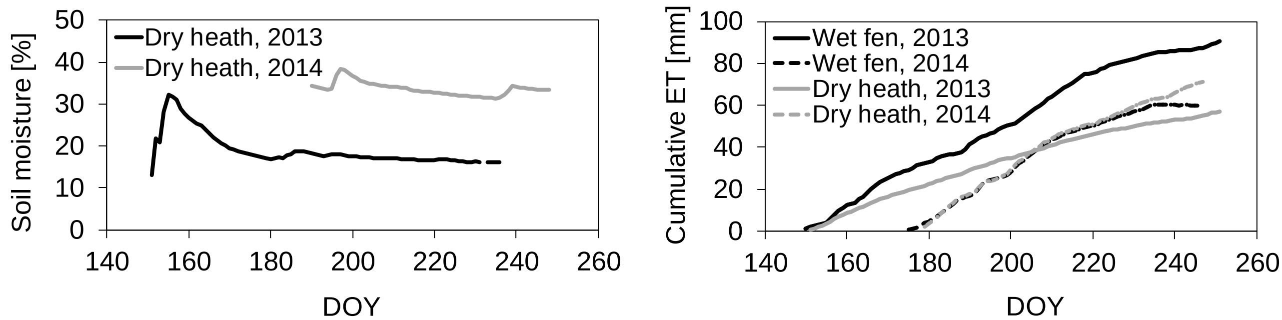


Figure ~~6b~~8: Development of soil moisture conditions (10 cm depth) and evapotranspiration (*ET*).

Mean daily soil moisture content at the dry heath (left) and cumulative evapotranspiration (*ET*) at the wet fen and dry heath during the growing season in 2013 ~~(left)~~ and 2014 (right).

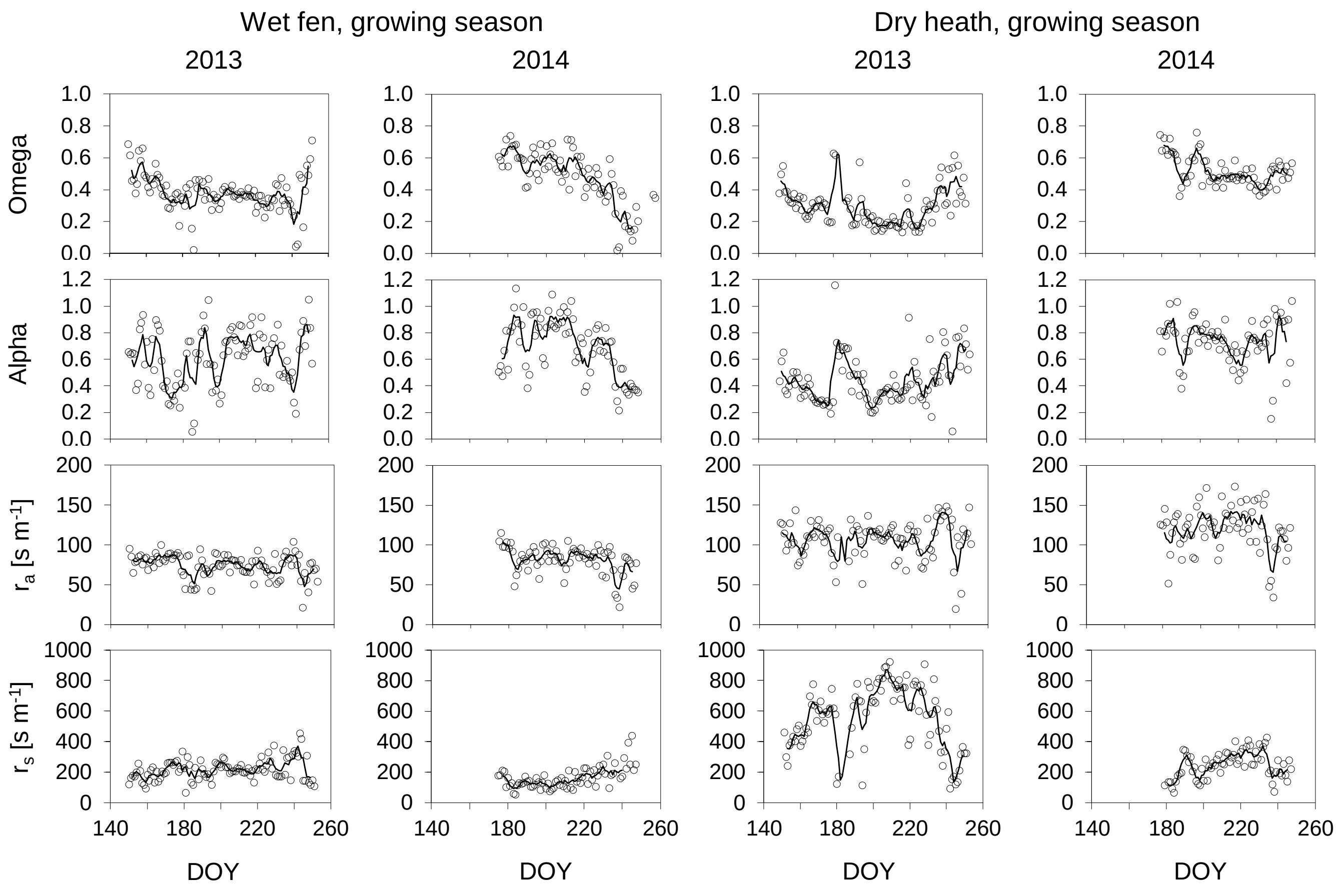
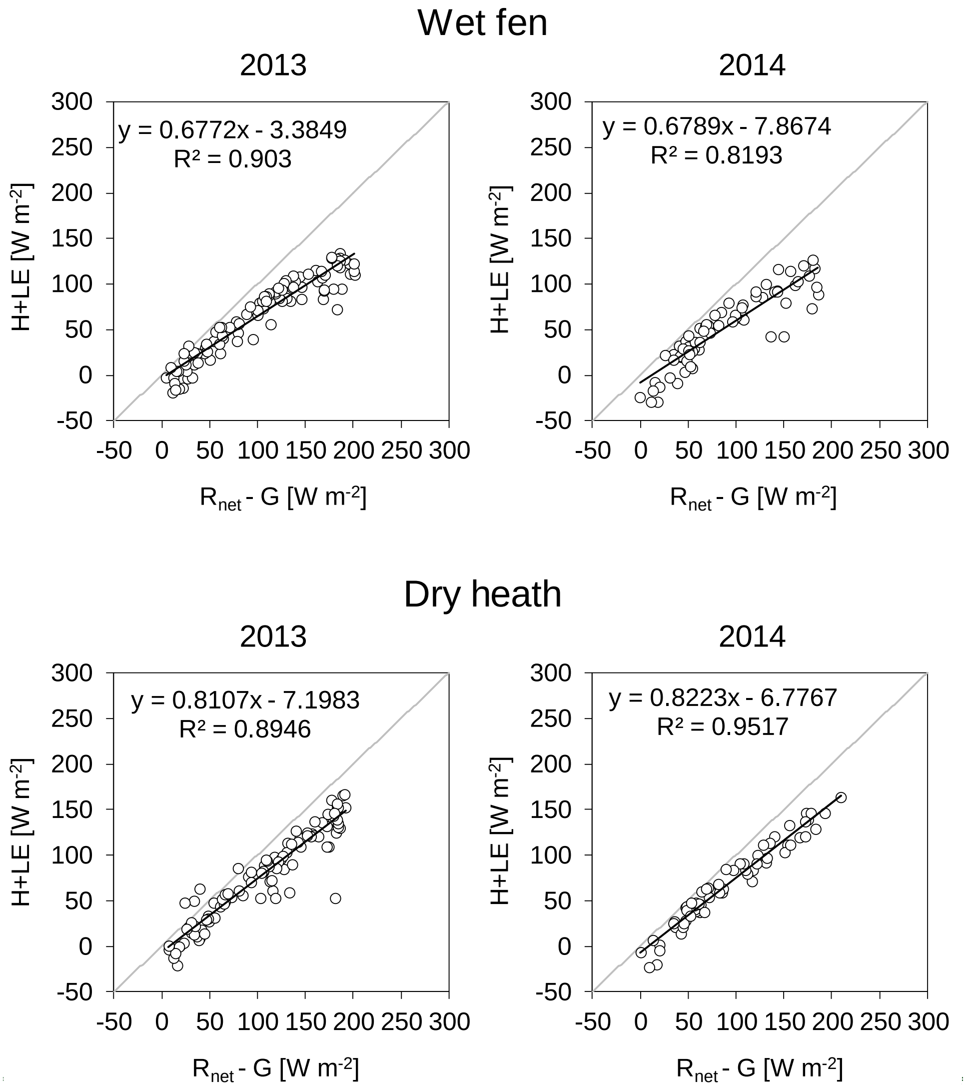


Figure ~~7~~9: Omega, alpha, aerodynamic resistance and surface resistance.

Mean daily (empty circles) and 5-day running mean (solid line) of McNaughton & Jarvis decoupling factor (Omega), Priestley and Taylor Alpha-value (Alpha), aerodynamic resistance (r_a) and surface resistance (r_s) at the wet fen (left) and dry heath (right) during the growing seasons in 2013 and 2014.



~~**Figure 8:** Energy balance closure.~~

~~Mean daily available energy ($R_{net} - G$) and turbulent heat fluxes ($H+LE$) at the wet fen (upper) and the dry heath (lower) during the observation periods in 2013 and 2014.~~

References

Aubinet, M., Vesala, T., and Papale, D.: Eddy Covariance A Practical Guide to Measurement and Data Analysis, Springer Netherlands, Dordrecht, 438 pp., 2012.

Bay, C.: Vegetation mapping of Zackenberg valley, Northeast Greenland, Polar Center & Botanical Museum, Copenhagen, 1998.

Becker, A., Finger, P., Meyer-Christoffer, A., Rudolf, B., Schamm, K., Schnieder, U., and Ziese, M.: A description of the global land-surface precipitation data products of the Global Precipitation Climatology Centre with sample applications including centennial (trend) analysis from 1901-present, Earth System Science Data, 5, 71-99, 10.5194/essd-5-71-2013, 2013.

Bintanja, R., and van der Linden, E. C.: The changing seasonal climate in the Arctic, Scientific Reports, 3, 1556, 10.1038/srep01556, 2013.

Bintanja, R., and Selten, F. M.: Future increases in Arctic precipitation linked to local evaporation and sea-ice retreat, Nature, 509, 479-482, 10.1038/nature13259, 2014.

Eddy covariance gap-filling & fux-partitioning tool: http://www.bgc-jena.mpg.de/~MDIwork/eddyproc/, access: 30 November 2015.

Boike, J., Wille, C., and Abnizova, A.: Climatology and summer energy and water balance of polygonal tundra in the Lena River Delta, Siberia, Journal of Geophysical Research, 113, G03025, 10.1029/2007 JG000540, 2008.

Bokhorst, S., Bjerke, J. W., Bowles, F. W., Melillo, J. M., Callaghan, T. V., and Phoenix, G. K.: Impacts of extreme winter warming in the sub-Arctic: growing season responses of dwarf shrub heathland, Global Change Biology, 14, 2603-2612, 10.1111/j.1365-2486.2008.01689.x, 2008.

Bokhorst, S., Bjerke, J. W., Street, I. E., Callaghan, T. V., and Phoenix, G. K.: Impacts of multiple extreme winter warming events on sub-Arctic heathland: Phenology, reproduction, growth, and CO2 flux responses, Global Change Biology, 17, 2817-2830, 10.1111/j.1365-2486.2011.02424.x, 2011.

Burba, G. G., McDermitt, D. K., Anderson, D. J., Furtaw, M. D., and Eckles, R. D.: Novel design of an enclosed CO2/H2O gas analyser for eddy covariance flux measurements, Tellus B, 62B, 743-748, 10.1111/j.1600-0889.2010.00468.x, 2010.

Callaghan, T. V., Björn, L. O., Chapin III, F. S., Chernov, Y. I., Christensen, T. R., Huntley, B., Ims, R., Johansson, M., Riedlinger, D. J., Jonasson, S., Matveyeva, N., Oechel, W., Panikov, N., and Shaver, G.: Chapter 7: Arctic tundra and polar desert ecosystems, in: Arctic Climate Impact Assessment, Cambridge University Press, Cambridge, 243-352, 2005.

Callaghan, T. V., Johansson, M., Anisimov, O., Christiansen, H. H., Instanes, A., Romanovsky, V., and Smith, S.: Chapter 4: Changing snow cover and its impacts, in: Snow, Water, Ice and Permafrost in the Arctic (SWIPA), Arcitc Monitoring and Assessment Programme (AMAP), Oslo, 1-58, 2011a.

Callaghan, T. V., Johansson, M., Brown, R. D., Groisman, P. Y., Labba, N., Radionov, V., Bradley, R., Blangy, S., Bulygina, O. N., Christensen, T. R., Colman, J. E., Essery, R. L. H., Forbes, B. C., Forchhammer, M. C., Golubev, V. N., Honrath, R. E., Juday, G. P., Meshcherskaya, A. V., Phoenix, G. K., Pomeroy, J., Rautio, A., Robinson, D. A., Schmidt, N. M., Serreze,

M. C., Shevchenko, V. P., Shiklomanov, A. I., Shmakin, A. B., Sköld, P., Sturm, M., Woo, M., and Wood, E. F.: Multiple effects of changes in arctic snow cover, AMBIO, 40, 32-45, 10.1007/s13280-011-0213-x, 2011b.

Chapin III, F. S., Shaver, G., Giblin, A. E., Nadelhoffer, K. J., and Laundre, J. A.: Response of arctic tundra to experimental and observed changes in climate, Ecology, 76, 694-711, 1995.

Chernov, Y. I.: The Living Tundra, Cambridge University Press, Cambridge, 228 pp., 1988.

Christiansen, H. H.: Meteorological control on interannual spatial and temporal variations in snow cover and ground thawing in two Northeast Greenlandic Circumpolar-Active-Layer-Monitoring (CALM) sites, Permafrost and Periglacial Processes, 15, 155-169, 10.1002/ppp.489, 2004.

Elberling, B., Tamstorf, M. P., Michelsen, A., Arndal, M. F., Sigsgaard, C., Illeris, L., Bay, C., Hansen, B., Christensen, T. R., Hansen, E. S., Jakobsen, B. H., and Beyens, L.: Soil and plant community-characteristics and dynamics at Zackenberg, Advances in Ecological Research, 40, 223-248, 10.1016/S0065-2504(07)00010-4, 2008.

Eugster, W., Rouse, W. R., Pielke, R. A., McFadden, J. P., Baldocchi, D. D., Kittel, T. G. F., Chapin, F. S., Liston, G. E., Vidale, P. L., Vaganov, E., and Chambers, S.: Land-atmosphere energy exchange in Arctic tundra and boreal forest: available data and feedbacks to climate, Global Change Biology, 6, 84-115, 2000.

Euskirchen, E. S., McGuire, A. D., Kicklighter, D. W., Zhuang, Q., Clein, J. S., Dargaville, R. J., Dye, D. G., Kimball, J. S., McDonald, K. C., Melillo, J. M., Romanovsky, V., and Smith, N. V.: Importance of recent shifts in soil thermal dynamics on growing season length, productivity, and carbon sequestration in terrestrial high-latitude ecosystems, Global Change Biology, 12, 731-750, 10.1111/j.1365-2486.2006.01113.x, 2006.

Falge, E., Baldocchi, D., Tenhunen, J., Aubinet, M., Bakwin, P., Berbigier, P., Bernhofer, C., Burba, G., Clement, R., Davis, K. J., Elbers, J. A., Goldstein, A. H., Grelle, A., Granier, A., Gundmundsson, J., Hollinger, D., Kowalski, A. S., Katul, G., Law, B. E., Malhi, Y., Meyers, T., Monson, R. K., Munger, J. W., Oechel, W., Tha Paw U, K., Pilegaard, K., Rannik, U., Rebmann, C., Suyker, A. E., Valentini, R., Wilson, K., and Wofsy, S.: Seasonality of ecosystem respiration and gross primary production as derived from FLUXNET measurements, Agricultural and Forest Meteorology, 113, 53-74, 2002.

Foken, T.: The energy balance closure problem: an overview, Ecological Applications, 18, 1351-1367, 2008.

Graversen, R. G., Mauritsen, T., Tjernström, M., Källén, E., and Svensson, G.: Vertical structure of recent Arctic warming, Nature, 541, 53-56, 10.1038/nature06502, 2008.

Groisman, P. Y., Karl, T. R., and Knight, R. W.: Changes of snow cover, temperature, and radiative heat balance over the Northern Hemisphere, Journal of Climate, 7, 1994.

Hanks, J. R., and Ashcroft, G. L.: Applied soil physics. Soil water and temperature applications, Springer, New York, 159 pp., 1980.

Hansen, B., Sigsgaard, C., Rasmussen, L. H., Cappelen, J., Hinkler, J., Mernild, S. H., Petersen, D., Tamstorf, M. P., Rasch, M., and Hasholt, B.: Present-day climate at Zackenberg, Advances in Ecological Research, 40, 111-149, 2008.

Hartman, D. L., Klein Tank, A. M. G., Rusticucci, M., Alexander, L. V., Brönnimann, S., Charabi, Y., Dentener, F. J., Dlugokencky, E. J., Easterling, D. R., Kaplan, A., Soden, B. J., Thorne, P. W., Wild, M., and Zhai, P. M.: Observations:

Atmosphere and Surface, in: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, 159-254, 2013.

Haslwanter, A., Hammerle, A., and Wohlfahrt, G.: Open-path vs. closed-path eddy covariance measurements of the net ecosystem carbon dioxide and water vapour exchange: A long-term perspective, Agricultural and Forest Meteorology 149, 291-302, 10.1016/j.agrformet.2008.08.011, 2009.

Jarvis, P. G., and McNaughton, K. G.: Stomatal control on transpiration: scaling up from leaf to region, Advances in Ecological Research, 15, 1-49, 1986.

Jentsch, A., Kreyling, J., and Beierkuhnlein, C.: A new generation of climate change experiments: events, not trends, Frontiers in Ecology and the Environment, 5 (7), 365-374, 10.1890/1540-9295(2007)5[365:ANGOCE]2.0.CO;2, 2007.

Kasurinen, V., Alfredsen, K., Kolari, P., Mammarella, I., Alekseychik, P., Rinne, J., Vesala, T., Bernier, P., Boike, J., Langer, M., Belelli Marchesini, L., van Huissteden, K., Dolman, H., Sachs, T., Ohta, T., Varlagin, A., Rocha, A., Arain, A., Oechel, W., Lund, M., Grelle, A., Lindroth, A., Black, A., Aurela, M., Laurila, T., Lohila, A., and Berninger, F.: Latent heat exchange in the boreal and arctic biomes, Global Change Biology, 20, 3439-3456, 10.1111/gcb.12640, 2014.

Kattsov, V. M., Källén, E., Cattle, H., Christensen, J., Drange, H., Hanssen-Bauer, I., Jóhannesen, T., Karol, I., Räisänen, J., Svensson, G., and Vavulin, S.: Chapter 7: Arctic tundra and polar desert ecosystems, in: Arctic Climate Impact Assessment, Cambridge University Press, Cambridge, 99-150, 2005.

Lafleur, M. P., and Rouse W. R.: The influence of surface cover and cliate on energy partitioning and evaporation in a subarctic wetland, Boundary-Layer Meteorology, 44, 327-347, 1988.

Langer, M., Westerman, S., Piel, K., and Boike, J.: The surface energy balance of a polygonal tundra site in northern Siberia - Part 1: Spring to fall, The Cryosphere, 5, 151-171, 10.5194/tc-5-151-2011, 2011.

Leuning, R., van Gorsel, E., Massman, W. J., and Isaac, P. R.: Reflections on the surface energy imbalance problem, Agricultural and Forest Meteorology, 156, 65-74, 10.1016/j.agrformet2011.12.002, 2012.

Liljedahl, A. K., Hinzman, L. D., Harazona, Y., Zona, D., Tweedie, C. E., Hollister, R. D., Engstrom, R., and Oechel, W.: Nonlinear controls on evapotranspiration in arctic coastal wetlands, Biogeosciences, 8, 3375-3389, 10.5194/bg-8-3375-2011, 2011.

Losch, R., and Tenhunen, J. D.: Stomatal responses to humidity – Phenomenon and mechanisms, in: Water deficits and plant growth, Cambridge University Press, Cambridge, 131-161, 1983.

Lund, M., Falk, J. M., Friborg, T., Mbufong, H. N., Sigsgaard, C., Soegaard, H., and Tamstorf, M. P.: Trends in CO2 exchange in a high Arctic tundra heath, 2000-2010, Journal of Geophysical Research, 117, G02001, 10.1029/2011JG001901, 2012.

Lund, M., Hansen, B., Pedersen, S. H., Stiegler, C., and Tamstorf, M. P.: Characteristics of summer-time energy exchange in a high Arctic tundra heath 2000-2010, Tellus B, 66, 21631, 10.3402/tellusb.v66.21631, 2014.

Massman, W. J., and Ibrom, A.: Attenuation of concentration fluctuations of water vapor and other trace gases in turbulent tube flow, Atmospheric Chemistry and Physics, 8, 6245-6259, Marchand, F. L., Kockelbergh, F., van de Vijver, B., Beyens, L., and Nijs, I.: Are heat and cold resistance of arctic species affected by successive extreme temperature events?, New Phytologist, 170, 291-300, 10.1111/j.1469-8137.2006.01659.x, 2005.

McBean, G., Alexseev, G., Chen, D., Førland, E., Fyfe, J., Groisman, P. Y., King, R., Melling, H., Vose, R., and Whitfield, P. H.: Arctic climate: past and present, in: Arctic Climate Impact Assessment - Scientific Report, Cambridge University Press, Cambridge, 21-60, 2005.

McFadden, J. P., Eugster, W., and Chapin III, F. S.: A regional study of the controls on water vapor and CO_2 exchange in Arctic tundra, Ecology, 84 (10), 2762-2776, 2003.

Monteith, J. L., and Unsworth, M. H.: Principles of environmental physics. Plants, animals, and the atmosphere, Academic Press, Oxford, 2013.

Mylius, M. R., Christensen, T. R., Hangaard, P., Hansen, B., Petersen, D., Tamstorf, M. P., Mastepanov, M., Sørensen, M. W., Petersen, L. G., Rasmussen, L. H., Sigsgaard, C., Skov, K., Abermann, J., and Lund, M.: Zackenberg Basic, The Climate Basis and GeoBasis programmes, Danish Centre for Environment and Energy, Roskilde, 130, 2014.

Nakićenović, N., Alcamo, J., Davis, G., de Vries, B., Fenhann, J., Gaffin, S., Gregory, K., Grübler, A., Jung, T.Y., Kram, T., La Rovere, E.L., Michaelis, L., Mori, S., Morita, T., Pepper, W., Pitcher, H., Price, L., Raihi, K., Roehrl, A., Rogner, H.H., Sankovski, A., Schlesinger, M., Shukla, P., Smith, S., Swart, R., van Rooijen, S., Victor, N. and Dadi, Z.: IPCC special report on emissions scenarios, Cambridge University Press, Cambridge, 2000.

Novik, K. A., Walker, J., Chan, W. S., Schmidt, A., Sobek, C., and Vose, J. M.: Eddy covariance measurements with a new fast-response, enclosed-path analyzer: Spectral characteristics and cross-system comparisons, Agricultural and Forest Meteorology, 181, 17-32, 10.1016/j.agrformet.2013.06.020, 2013.

Overpeck, J., Hughen, K., Hardy, D., Bradley, R., Case, R., Douglas, M., Finney, B., Gajewski, K., Jacoby, G., Jennings, A., Lamoureux, S., Lasca, A., MacDonald, G., Moore, J., Retelle, M., Smith, S., Wolfe, A., and Zielinski, G.: Arctic environmental change for the last four centuries, Science, 278, 1251-1256, 10.1126/science.278.5341.1251, 1997.

Pedersen, M. R., Christensen, T. R., Hangaard, P., Hansen, B., Jackowicz-Korczynski, M., Larsen, M., Lund, M., Mastepanov, M., Petersen, D., Højlund Pedersen, S., Pedersen, L. G., Rasmussen, L. H., Sigsgaard, C., Skov, K., Stiegler, C., Thorsøe, K., and Tamstorf, M. P.: Zackenberg Basic: The ClimateBasis and GeoBasis programme, Danish Centre for Environment and Energy, Roskilde, 13-29, 2012.

Priestley, C. H. B., and Taylor, R. J.: On the assessment of surface heat flux and evaporation using large-scale parameters, Monthly Weather Review, 100, 81-92, 1972.

Rawlins, M. A., Steele, M., Holland, M. M., Adam, J. C., Cherry, J. E., Francis, J. A., Groisman, P. Y., Hinzman, L. D., Huntington, T. G., Kane, D. L., Kimball, J. S., Kwok, R., Lammers, R. B., Lee, C. M., Lettenmaier, D. P., McDonald, K. C., Podest, E., Pundsack, J. W., Rudels, B., Serreze, M. C., Shiklomanov, A. I., Skagseth, Ø., Troy, T. J., Vörösmarty, C. J., Wensnahan, M., Wood, E. F., Woodgate, R., Yang, D., Zhang, K., and Zhang, T.: Analysis of the Arctic system for freshwater cycle intensification: Observations and expectations, Journal of Climate, 23, 5715-5737, 10.1175/2010JCLI3421.1, 2010.

Reichstein, M., Falge, E., Baldocchi, D., Papale, D., Aubinet, M., Berbigier, P., bernhofer, C., Buchmann, N., Gilmanov, T., Granier, A., Grünwald, T., Havránková, K., Ilvesniemi, H., Janous, D., Knohl, A., Laurila, T., Lohila, A., Loustau, D., Matteucci, G., Meyers, T., Miglietta, F., Ourcival, J. M., Pumpanen, J., Rambal, S., Rotenberg, E., Sanz, M., Tenhunen, J., Seufert, G., Vaccari, F., Vesala, T., Yakir, D., and Valentini, R.: On the separation of net ecosystem exchange into assimilation and ecosystem respiration: review and improved algorithm, Global Change Biology, 11, 1424-1439, 2005.

Rouse, W. R.: The energy and water balance of high-latitude wetlands: controls and extrapolation, Global Change Biology 6 (1), 59-68, 2000.

Screen, J. A., and Simmonds, I.: The central role of diminishing sea ice in recent Arctic temperature amplification, Nature, 464, 1334-1337, 10.1038/nature09051, 2010.

Shuttleworth, W. J.: Putting the 'vap' into evaporation, Hydrology and Earth System Sciences, 11, 210-244, 2007.

Soegaard, H., Hasholt, B., and Nordstroem, C.: Surface energy- and water balance in a high-arctic environment in NE Greenland, Theoretical and Applied Climatology, 70, 35-51, 2001.

Stendel, M., Hesselbjerg Christiensen, J., Aðalgeirsdóttir, G., Kliem, N., and Drews, M.: Regional climate change for Greenland and surrounding seas, Danish Climate Centre Report, Copenhagen, 2007.

Stocker, T. F., Qin, D., Plattner, G. K., Tinor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M.: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, 2013.

Stoy, P., Mauder, M., Foken, T., Marcolla, B., Boegh, E., Ibrom, A., Altaf Arain, M., Arneth, A., Aurela, M., Bernhofer, C., Cescatti, A., Dellwik, E., Duce, P., Gianelle, D., van Gorsel, E., Kiely, G., Knohl, A., Margolis, H., McGaughey, H., Merbold, L., Montagnani, L., Papale, D., Reichstein, M., Saunders, M., Serrano-Ortiz, P., Sottocornola, M., Spano, D., Vaccari, F., and Varlagin, A.: A data-driven analysis of energy balance closure across FLUXNET research sites: The role of landscape scale heterogeneity, Agricultural and Forest Meteorology, 171-172, 137-152, 10.1016/j.agrformet.2012.11.004, 2013.

Sturm, M., and Douglas, T.: Changing snow and shrub conditions affect albedo with global implications, Journal of Geophysical Research, 110, G01004, 10.1029/2005JG000013, 2005.

Su, H.-B., Schmid, H. P. Grimmond, C. S. B., Vogel, C. S., and Oliphant, A. J.: Spectral characteristics and correction of long-term eddy-covariance measurements over two mixed hardwood forests in non-flat terrain, Boundary-Layer Meteorology, 110, 213-253, 2004.

Tagesson, T., Mölder, M., Mastepanov, M., Sigsgaard, C., Tamstorf, M. P., Lund, M., Falk, J. M., Lindroth, A., Christensen, T. R., and St~~T~~röm, L.: Land-atmosphere exchange of methane from soil thawing to soil freezing in a high-Arctic wet tundra ecosystem, Global Change Biology, 18, 1928-1940, 10.1111/j.1365-2486.2012.02647.x, 2012.

Walker, D. A., Billings, W. D., and De Molenaar, J. G.: Snow-vegetation interactions in tundra environments, in: Snow Ecology: an interdisciplinary examination of snow-covered ecosystems, edited by: Jones, H. G., Pomeroy, J., Walker, D. A., and Hoham, R. W., Cambridge University Press, Cambridge, 266-324, 2001.

Warren, S. G.: Optical properties of snow, Reviews of Geophysics and Space Physics, 20, 67-89, 1982.

Westerman, S., Lüers, J., Langer, M., Piel, K., and Boike, J.: The annual surface energy budget of a high-arctic permafrost site on Svalbard, Norway, The Cryosphere, 3, 245-263, 2009.

Woo, M. K., Lewkowicz, A. G., and Rouse, W. R.: Response of the Canadian permafrost environment to climatic change, Physical Geography, 134, 287-317, 1992.

Wyngaard, J. C., and Cote, O. R.: Cospectral similarity in atmospheric surface-layer, Quarterly Journal of the Royal Meteorological Society, 98 (417), 590-603, 1972.

Tables

Table 1: List of parameters and symbols.

Name	Unit	Explanation	Location
$RS\downarrow$	W m^{-2}	Incoming shortwave radiation	Wet fen, dry heath, Asiaq-tower
$RS\uparrow$	W m^{-2}	Outgoing shortwave radiation	Wet fen, dry heath, Asiaq-tower
$RL\downarrow$	W m^{-2}	Downwelling longwave radiation	Wet fen, dry heath, Asiaq-tower
$RL\uparrow$	W m^{-2}	Upwelling longwave radiation	Wet fen, dry heath, Asiaq-tower
RS_{net}	W m^{-2}	Net solar radiation [Eq. 2]	Wet fen, dry heath, Asiaq-tower
RL_{net}	W m^{-2}	Net longwave radiation [Eq. 2]	Wet fen, dry heath, Asiaq-tower
R_{net}	W m^{-2}	Net radiation [Eq. 2]	Wet fen, dry heath, Asiaq-tower
Albedo		Surface albedo	Wet fen, dry heath, Asiaq-tower
T_a	°C	Air temperature	Wet fen, dry heath, Asiaq-tower
$T_{surf.}$	°C	Snow surface temperature	Wet fen, dry heath, Asiaq-tower
T_s	°C	Soil temperature at 2 and 10 cm depth	Wet fen, dry heath
H	W m^{-2}	Sensible heat flux	Wet fen, dry heath
LE	W m^{-2}	Latent heat flux	Wet fen, dry heath
G	W m^{-2}	Ground heat flux	Wet fen, dry heath
H/LE		Bowen ratio	Wet fen, dry heath
Snow depth	m	Snow depth	Wet fen, dry heath, Asiaq-tower
Soil moisture	%	Soil moisture content	Wet fen, dry heath
Mixing ratio	g kg^{-1}	Atmospheric mixing ratio	Wet fen, dry heath
RH	%	Relative humidity	Wet fen, dry heath, Asiaq-tower
VPD	hPa	Atmospheric vapour pressure deficit	Wet fen, dry heath, Asiaq-tower
ET	mm d^{-1}	Evapotranspiration	Wet fen, dry heath
Precip.	mm	Precipitation	Asiaq-tower
α		Priestley-Taylor coefficient [Eq. 8]	Wet fen, dry heath

u	m s^{-1}	Wind speed	Wet fen, dry heath
u_*	m s^{-1}	Friction velocity	Wet fen, dry heath
r_a	s m^{-1}	Aerodynamic resistance [Eq. 5]	Wet fen, dry heath
–	s m^{-1}	Surface resistance [Eq. 6]	Wet fen, dry heath
Ω		McNaughton & Jarvis Omega value [Eq. 7]	Wet fen, dry heath
NDVI		Normalized Difference Vegetation Index	Wet fen

~~Table 1~~**Table 2:** Summary of polar night and pre-melt season.

List of mean daily radiation components and environmental characteristics during the polar night seasons and pre-melt seasons in 2012/13 and 2013/14.

	Polar night				Pre-melt season			
	2012/13		2013/14		2013		2014	
Duration	10 Nov. – 4 Feb.		10 Nov. – 4 Feb.		5 Feb. – 12 May		5 Feb. – 5 May	
	Average (Standard error)	~~St. dev.~~Range	Average (Standard error)	Range~~St. dev.~~	Average (Standard error)	~~St. dev.~~Range	Average (Standard error)	~~St. dev.~~Range
$RS\downarrow$ (W m^{-2})	0	0	0	0	99.2 (8.6)	~~83.9~~0 – 586.9	87.0 (8.3)	0 – 577.0~~78.6~~
$RS\uparrow$ (W m^{-2})	0	0	0	0	81.9 (6.8)	0 – 449.5~~66.2~~	76.4 (7.0)	0 – 480.0~~65.7~~
$RL\downarrow$ (W m^{-2})	193.2 (3.9)	133.4 – 293.9~~34.4~~	213.1 (4.7)	140.7 – 305.7~~43.6~~	188.3 (3.1)	142.1 – 269.8~~30.3~~	194.6 (3.3)	141.3 – 280.5~~31.5~~
$RL\uparrow$ (W m^{-2})	219.2 (2.3)	176.9 – 295.1~~21.7~~	237.1 (3.1)	190.4 – 307.7~~29.1~~	224.1 (2.6)	175.5 – 276.5~~25.8~~	225.7 (2.5)	173.3 – 285.8~~23.5~~
RS_{net} (W m^{-2})	0	0	0	0	17.1 (1.9)	0 – 65.8~~18.1~~	11.0 (1.4)	0 – 50.7~~13.5~~
RL_{net} (W m^{-2})	-27.0 (1.8)	~~16.5~~-54.8 – 10.3	-24.1 (2.1)	~~19.2~~-69.6 – 7.7	-35.4 (2.1)	-67. 4 – 17.5~~20.5~~	-31.1 (1.9)	-62. 7 – 14.2~~18.2~~
R_{net} (W m^{-2})	-27.0 (1.8)	-54.8 – 10.3~~16.5~~	-24.1 (2.1)	69.6 – 7.7~~19.2~~	-18.0 (1.8)	-44.0 – 37.3~~17.4~~	-20.5 (1.7)	-48.2 – 15.3~~15.4~~
$T_{a\cancel{ir}}$ (°C)	-19.2 (0.6)	-28.7 – -4.8~~5.4~~	-15.2 (0.7)	-27.8 – -0.8~~6.5~~	-18.1 (0.7)	-23.5 – -6.5~~6.4~~	-17.6 (0.6)	-29.4 – -3.8~~55.4~~
$T_{surf.}$ (°C) ~~1~~	-24.1 (0.6)	-36.8 – -4.6~~6.0~~	-19.2 (0.8)	-32.4 – -1.7~~7.6~~	-22.8 (0.7)	-37.3 – -9.0~~7.2~~	-22.3 (0.7)	-38.0 – -6.7~~6.5~~

Air pressure (hPa)	1010.0 (1.1)	983.1 – 1030.6~~10.0~~	1003.5 (1.2)	~~11.0~~956.9 – 1021.3	1019.1 (1.2)	999.1 – 1050.0~~12.0~~	1007.0 (1.1)	975. 5 – 1030.4~~10.6~~

~~[1]Snow surface temperature~~

~~Table 2~~**Table 3:** Summary of snow melt period.

List of mean daily surface energy balance and environmental characteristics during the snow melt period in 2013 and 2014 at the wet fen and dry heath site.

	Wet fen, 2013		Wet fen, 2014		Dry heath, 2013		Dry heath, 2014	
Duration	13 May – 29 May		6 May – 23 June		13 May – 30 May		6 May – 27 June	
	Average (Standard error)	Range~~St. dev.~~	Average (Standard error)	~~St. dev.~~Range	Average (Standard error)	~~St. dev.~~Range	Average (Standard error)	Range~~St. dev.~~
$RS\downarrow$ (W m^{-2})	260.3 (19.3)	111.0 – 355.9~~84.1~~	292.4 (9.6)	~~67.0~~105.7 – 387.9	252.7 (17.6)	113.4 – 340.6~~76.6~~	290.5 (8.7)	108.7 – 380.5~~63.2~~
$RS\uparrow$ (W m^{-2})	134.7 (9.4)	68.9 – 204.6~~41.1~~	205.7 (11.2)	14.4 – 273.5~~78.4~~	146.8 (11.1)	44.2 – 213.0~~48.3~~	213.2 (10.1)	27.1 – 276.4~~73.8~~
$RL\downarrow$ (W m^{-2})	272.9 (5.6)	237.5 – 314.6~~24.5~~	275.3 (4.8)	209.6 – 333.3~~33.8~~	251.1 (6.3)	213.7 – 295.6~~27.2~~	276.9 (4.7)	208.1 – 333.6~~34.0~~
$RL\uparrow$ (W m^{-2})	320.3 (2.3)	309.5 – 343.3~~9.9~~	314.1 (3.1)	264.3 – 343.4~~21.7~~	302.9 (2.3)	293.5 – 328.5~~9.9~~	316.1 (3.1)	263.5 – 363.2~~22.7~~
RS_{net} (W m^{-2})	125.5 (18.5)	29.7 – 283.8~~80.8~~	86.7 (7.8)	18.6 – 248.9~~54.5~~	105.9 (15.9)	24.5 – 259.0~~69.4~~	77.3 (7.9)	15.1 – 321.5~~57.2~~
RL_{net} (W m^{-2})	-47.4 (6.4)	-83.3 - -6.6~~27.7~~	-38.8 (2.6)	-69.6 - -2.9~~18.4~~	-51.7 (7.0)	-97.4 - -7.3~~30.3~~	-39.2 (2.8)	-80.2 - -1.9~~20.2~~
R_{net} (W m^{-2})	78.1 (13.0)	18.6 – 200.5~~56.6~~	47.9 (8.2)	-8.1 – 192.6~~57.3~~	54.2 (10.1)	12.8 – 168.2~~44.1~~	38.1 (7.7)	-14.3 – 241.4~~56.0~~
Albedo	0.57 (0.03)	0.31 – 0.78~~0.17~~	0.68 (0.02)	00.26 – 0.90~~.24~~	0.63 (0.04)	0.17 – 0.80~~0.17~~	0.73 (0.01)	0.47 – 0.92~~0.19~~
H (W m^{-2})	7.6 (4.3)	-9.1 – 52.8~~18.8~~	-	-	25.0 (6.5)	-4.8 – 99.5~~28.5~~	-	-
LE (W m^{-2})	15.6 (2.2)	3.3 – 40.2~~9.7~~	-	-	14.9 (1.8)	3.5 – 30.2~~8.0~~	-	-

G (W m^{-2})	8.4 (1.2)	4.0 – 23.0~~5.0~~	7.2 (1.2)	-2.3 – 38.3~~7.9~~	5.1 (0.4)	1.7 – 8.5~~1.9~~	5.1 (1.1)	-1.8 – 37.1~~7.4~~
T_{a}~~ir~~ (°C)	-1.6 (0.4)	-3.7 – 3.0~~1.7~~	-1.4 (0.7)	-10.7 – 9.6~~4.8~~	-1.6 (0.4)	-3.7 – 3.0~~1.7~~	-1.2 (0.6)	-10.7 – 9.6~~4.6~~
T_{s}~~oil~~ (°C) [1]	-6.8 (0.6)	-10.5 – -0.3~~2.7~~	-6.3 (0.6)	-11.8 – 1.7~~4.4~~	-2.4 (0.5)	-7.7 – 0-3~~2.2~~	-4.8 (0.7)	-11.4 – 3.5~~4.8~~
Air pressure (hPa)	1017.0 (1.0)	1011.3 – 1025.3~~4.2~~	1014.9 (0.9)	1000.4 – 1028.0~~6.1~~	1017.0 (1.0)	1011.3 – 1025.3~~4.2~~	1014.5 (0.9)	1000.4 – 1028.0~~6.1~~
ET	0.51 (0.08)	0.12 – 1.41	-	-	0.52 (0.07)	0.13 – 1.06	-	-

[1]~~Soil temperature~~ Measured at 2 cm depth

~~**Table 3**~~**Table 4:** Summary of growing season.

List of mean daily surface energy balance and environmental characteristics during the growing seasons in 2013 and 2014 at the wet fen and dry heath site.

	Wet fen				Dry heath			
	2013		2014		2013		2014	
Duration	30 May – 8 Sept.		24 June – 4 Sept.		31 May – 8 Sept.		28 June – 4 Sept.	
	Average (Standard error)	~~St. dev~~Range~~.~~	Average (Standard error)	Range~~St. dev.~~	Average (Standard error)	~~St. dev.~~Range	Average (Standard error)	~~St. dev.~~Range
RS↓ (W m^{-2})	211.5 (10.9)	17.7 – 369.3~~10.0~~	179.0 (10.8)	17.4 – 375.1~~92.1~~	210.4 (10.9)	15.7 – 369.6~~109.7~~	171.2 (10.7)	15.7 – 370.6~~88.6~~
RL↑ (W m^{-2})	361.7 (1.4)	329.2 – 390.6~~14.0~~	364.4 (1.6)	340.1 – 398.2~~13.9~~	356.0 (1.5)	319.4 – 381.7~~13.6~~	366.2 (1.8)	340.3 – 399.9~~14.9~~
RL↓ (W m^{-2})	305.1 (2.2)	257.4 – 350.9~~21.8~~	314.0 (2.5)	26.08 – 357.0~~21.4~~	291.5 (2.8)	226.5 – 348.6~~27.8~~	313.6 (2.6)	261.4 – 356.5~~22.0~~
RS↑ (W m^{-2})	41.1 (2.2)	2.1 – 83.1~~22.5~~	28.3 (1.8)	~~15.3~~2.1 – 56.9	40.7 (2.2)	2.1 – 74.9~~22.2~~	19.7 (1.3)	0.7 – 43.9~~11.0~~
RS_{net} (W m^{-2})	170.4 (8.7)	15.7 – 298.3~~88.0~~	150.7 (9.1)	15.3 – 322.2~~78.5~~	169.7 (8.8)	13.6 – 298.3~~88.0~~	151.5 (9.4)	15.0 – 336.4~~78.4~~
RL_{net} (W m^{-2})	-56.6 (2.8)	-98.4 - - 2.4~~27.9~~	-50.5 (3.1)	-98.4 - - 4.5~~26.2~~	-71.4 (3.5)	-111.9 - - 4.4~~31.3~~	-52.6 (3.4)	-104.8 - - 4.5~~27.9~~
R_{net} (W m^{-2})	114.2 (6.4)	5.2 – 208.3~~64.8~~	100.2 (7.1)	-2.0 – 231.9~~60.2~~	111.4 (6.1)	6.3 – 201.3~~60.9~~	98.9 (7.0)	0.3 – 246.8~~57.9~~
Albedo	0.20 (0.003)	0.13 – 0.31~~0.03~~	0.17 (0.005)	0.07 – 0.28~~0.05~~	0.16 (0.004)	0.08 – 0.32~~0.04~~	0.13 (0.006)	0.06 – 0.26~~0.05~~
H (W m^{-2})	41.5 (3.4)	-23.8 – 101.7~~33.9~~	26.6 (2.9)	-29.5 – 85.1~~24.4~~	62.6 (4.6)	-25.9 – 149.5~~46.1~~	36.9 (3.8)	-29.6 – 107.7~~31.3~~

LE (W m^{-2})	25.2 (1.5)	1.8 – 57.2~~15.1~~	23.3 (2.0)	-5.9 – 65.7~~17.4~~	16.0 (0.6)	3.6 – 39.1~~6.2~~	29.3 (1.8)	5.9 – 69.0~~15.3~~
G (W m^{-2})	10.8 (0.9)	-3.9 – 56.5~~8.8~~	15.2 (1.3)	-2.1 – 47.5~~10.8~~	5.6 (0.3)	-1.5 – 16.9~~3.5~~	10.1 (0.9)	-0.4 – 37.3~~7.2~~
H/LE	1.6 (0.1)	0.16 – 4.3~~1.3~~	1.1 (0.1)	0.28 – 3.09~~0.8~~	4.3 (0.2)	0.03 – 8.3~~2.1~~	1.6 (0.1)	0.28 – 3.09~~0.7~~
H/R_{net}	0.36 (0.01)	0.03 – 0.57~~12~~	0.27 (0.01)	0.01 – 0.40~~0.11~~	0.54 (0.02)	0.11 – 0.88~~0.18~~	0.38 (0.01)	0.05 – 0.56~~14~~
LE/R_{net}	0.22 (0.01)	0.04 – 0.61~~14~~	0.23 (0.01)	0.01 – 0.35~~11~~	0.18 (0.01)	0.08 – 0.56~~13~~	0.33 (0.01)	0.12 – 0.70~~13~~
G/R_{net}	0.12 (0.01)	0.04 – 0.61~~0.08~~	0.17 (0.01)	0.01 – 0.35~~0.10~~	0.05 (0.003)	0.07 – 0.56~~03~~	0.10 (0.01)	0.12 – 0.70~~04~~
$T_{a\cancel{ir}}$ (°C)	5.3 (0.3)	0.4 – 11.9~~2.9~~	5.8 (0.3)	0.5 – 12.9~~2.7~~	5.3 (0.3)	0.4 – 11.9~~2.9~~	6.1 (0.3)	2.1 – 12.9~~2.5~~
$T_{s\cancel{oil}}$ (°C) [1]	4.0 (0.3)	-2.0 – 8.3~~2.1~~	5.0 (0.2)	-0.6 – 9.6~~2.5~~	-	-	3.3 (0.2)	-0.5 – 6.5~~1.6~~
Soil moisture (%)	-	-	-	-	19.0 (0.4)	13.1 – 32.2~~3.9~~	33.6 (0.2)	31.4 – 38.3~~1.6~~
Air pressure (hPa)	1004.4 (0.7)	989.4 – 1018.3~~6.6~~	1009.9 (0.6)	999.6 – 1019.3~~4.8~~	1004.3 (0.7)	989.4 – 1018.3~~6.6~~	1009.9 (0.6)	999.6 – 1019.3~~4.9~~
Mixing ratio (g kg^{-1})	6.6 (0.2)	4.1 – 10.9~~1.7~~	6.5 (0.2)	4.2 – 11.2~~1.5~~	6.6 (0.2)	4.1 – 10.9~~1.7~~	6.6 (0.2)	4.6 – 11.2~~1.4~~
RH (%)	71.1 (1.6)	33.9 – 97.2~~16.3~~	76.5 (1.8)	42.4 – 98.6~~15.7~~	71.2 (1.6)	33.9 – 97.1~~16.3~~	75.5 (1.9)	42.4 – 98.6~~15.5~~
VPD (hPa)	2.4 (0.2)	0.3 – 6.7~~1.7~~	2.0 (0.2)	0.1 – 6.5~~1.5~~	2.4 (0.2)	0.3 – 6.7~~1.7~~	2.2 (0.2)	0.1 – 6.5~~1.5~~
ET (mm d^{-1})	0.89 (0.05)	0.06 – 2.05~~3~~	0.82 (0.07)	-0.21 – 2.31~~0.61~~	0.56 (0.02)	0.13 – 1.38~~0.22~~	1.03 (0.06)	0.21 – 2.43~~54~~

α	0.60 (0.02)	0.06 – 1.05~~21~~	0.69 (0.03)	0.22 – 1.14~~22~~	0.44 (0.02)	0.06 – 1.16~~18~~	0.74 (0.02)	0.15 – 1.04~~.17~~
u (m s^{-1})~~[2]~~	2.7 (0.1)	1.4 – 11.0~~1.4~~	2.4 (0.2)	1.0 – 9.9~~1.5~~	2.8 (0.2)	1.4 – 12.4~~1.6~~	2.5 (0.2)	1.0 – 10.3~~1.5~~
u_* (m s^{-1})~~[3]~~	0.25 (0.01)	0.12 – 0.91~~0.11~~	0.22 (0.02)	0.09 – 0.95~~0.15~~	0.24 (0.02)	0.09 – 1.12~~0.15~~	0.20 (0.01)	0.09 – 0.80~~0.12~~
r_a (s m^{-1})	74.2 (0.5)	4.8 – 159.6~~30.8~~	81.5 (0.7)	5.2 – 159.4~~34.2~~	107.4 (1.0)	4.4 – 337.3~~63.9~~	119.7 (1.3)	7.2 – 336.7~~67.6~~
r_s (s m^{-1})	217.7 (7.0)	65.5 – 455.0~~70.1~~	165.4 (8.4)	52.5 – 441.5~~70.9~~	555.7 (21.9)	93.2 – 922.9~~214.5~~	246.7 (10.8)	64.2 – 428.1~~88.8~~
Ω~~[9]~~	0.38~~48~~ (0.01)	~~0.17~~0.02 – 0.71	0.4~~3~~8 (0.02)	0.01 – 0.74~~12~~	0.30~~52~~ (0.01)	0.14 – 0.63~~0.09~~	0.52~~30~~ (0.01)	0.36 – 0.76~~12~~
NDVI	0.45 (0.004)	0.01 – 0.68	0.49 (0.006)	0.03 – 0.74)	-	-	-	-

[1]Measured at 10 cm depth~~, [2]Wind speed, [3]Friction velocity~~