HESS-2014-195. Response to review by Martijn Westhoff

We thank the Reviewer for his constructive comments on our manuscript, we have found them to be very useful. We are pleased that he agrees with the general findings and recognises that the manuscript demonstrates the first explicit conceptualisation of processes by which cooling gradients develop beneath forest canopies, although we recognise (and indeed did not claim) that it is not the first study to have considered the effects of advected heat in a river temperature model. He recommended revisions be made to the manuscript prior to publication. We address each of these comments below together with suggestions for proposed revisions.

1. *In this study, the authors investigate the causes of often observed, negative longitudinal water temperature gradients under dense canopies. They do this by combining a steady state flow model with an energy balance model and came to the conclusion that the negative longitudinal temperature gradient observed at a moment in time is caused by advective heat transport of cooler upstream water.*

The Reviewer's description of the study is broadly correct, however we did not investigate processes under 'dense canopies' and we do not suggest this in the manuscript. The reach is characterised by patchy semi-natural riparian forest of highly variable density. Figure 5 demonstrates the variability in measured canopy density at 5 m intervals throughout the reach and Figure 4 demonstrates choice examples pictorially. Furthermore, we conclude that the observed temperature gradients are generated from the combination of advected heat and crucially, substantially lower heat gains in the shaded reach. Importantly we demonstrate that cooling in the reach during daylight hours does not generate the gradients.

2. *I do agree with their general findings, but there are several issues that need more attention before publication is warranted. The most important three are missing literature, the development of the temperature model and the way the data is smoothed or interpolated.*

Thank you, we are pleased that the Reviewer agrees with our findings. We are also grateful to the Reviewer for suggesting additional literature (of which we were unaware at the time of submission) that considers the role of advection in unforested reaches and in which hyporheic exchanges are significant. We are more than happy to add these references to the paper and to identify that previous studies have considered the effects of advected heat under different environmental settings. Clearly the hydrological and climatological conditions in these studies contrast with ours, given the importance of riparian shading, and the lack substantial groundwater inflows or evidence for significant hyporheic exchange in this study. We also thank the Reviewer for identifying that our methods require clarification and revision in some places. We address these three issues in further detail below.

3. ***Missing literature***
   There is a whole bunch of literature on stream temperature models, while only a very small amount has been mentioned. Especially the study of Roth et al. (2010) deserves some attention since it also uses an energy balance based stream temperature model to investigate the effect of riparian vegetation.

We are aware of the existence of the large volume of literature on stream temperature models. However, only the most recent studies were cited because the focus of the study was not the development of a new model. Rather, it was to explain the processes by which instantaneous cooling gradients are generated in forested reaches in the absence of groundwater inputs. We believe that we make this clear throughout. The study by Roth *et al.* (2010) certainly warrants citation and we will do that, however it does not investigate the processes producing cooling effects. We elaborate on the importance of understanding processes in response to Point 4.

4. *In the introduction, the authors mainly focus on Brown (1971) and Story et al. (2003) who attribute cooling gradients to groundwater input. It is correct that these studies did not explicitly explained their observed cooling gradient to advection of cooler upstream water, but because they included an advection term in their models, this effect was already implicitly taken into account (but apparently advection alone was not enough to explain the complete cooling gradient). Many other temperature models also have this advection in and thus take this effect implicitely into account as well (e.g. Bartholow, 2000; Boyd and Kasper, 2003; Foreman et al., 1997, 2001; Sinokrot and Stefan, 1993; Kim and Chapra, 1997; Westhoff et al., 2007; 2010; Younus et al., 2000 and several others).*

We disagree that Story et al. (2003) state explicitly that 'advection alone was not enough to explain the complete cooling gradient'. We refer the Reviewer to Story et al. (2003) and the section titled '*Processes controlling downstream changes at B3*' where they state that 'bed heat conduction and hyporheic exchange accounted for ~60% of the total cooling effect, with groundwater inflow accounting for the rest'. Regardless, as the Reviewer states, cooling processes have not been explained explicitly to date. A current review of the literature would suggest that downstream cooling in forested reaches has been observed only where groundwater inflows occur or that streams genuinely cool (loose heat) in forested reaches. Our manuscript sought to establish and explicitly state the processes and conditions under which negative downstream temperature gradients could occur within forested reaches in the absence of major groundwater inflows (which also heavily influence streambed temperature and thus the effects of hyporheic exchange).

This understanding of processes is essential because energy balance models and associated datasets are rarely available to stream managers when making decisions on afforesting reaches to mitigate against water temperature maxima. Yet the processes invoked will affect the efficacy of land management decisions. Therefore, it is critical that process based information is available to them. Thus, the information we provide in this manuscript will contribute to informed riparian planting, as stated in the Introduction (Page 6444 Lines 13- 16) and Conclusions (Page 6450, Line 26 to Page 6451, Line 4) of our original submission.

5. *Besides these, Westhoff et al. (2011) also showed that in their case study, the longitudinal gradient could not be explained by the energy balance (and since advection of cooler water could not explain the complete bias either, they attributed it to hyporheic exchange).*

Again, we thank the Reviewer for bringing this paper to our attention. It is a very interesting approach for investigating the potential influence of hyporheic exchange on stream temperature and we agree that we shall be sure to cite it where relevant. However, it was also conducted in a very different environmental setting and does not consider stream temperature processes as water transitions from open moorland areas to forested reaches, as is the particular focus of our paper. Under such circumstances, spatial variation in energy exchange processes at the stream-air interface and advected heat are both important in determining observed patterns of stream temperature without necessarily requiring significant groundwater or hyporheic influences.

6. *So the advective cooling has already been taken into account several times and the authors have to make that clear. So the novelty is not the fact that this manuscript is the first to have that included, but merely that it is the first time that this effect is emphasized.*

We are confused as to where this comment has come from. Nowhere in the manuscript do we claim to be the first authors to discuss the role of advection in determining stream temperature. We will be happy to include further citations to papers concerned with the role of advective processes under different environmental conditions to ensure that there are no further misunderstandings on this particular issue. However, as the Reviewer states, we are the first to conceptualise explicitly the processes by which advection contributes to the development of cooling gradients under the transition from open moorland to forest canopies. Consequently our study is a novel contribution to the existing literature and of value to river managers in clarifying the processes that generate frequently reported temperature gradients.

7. **Temperature Model**
   I also have several questions marks about the temperature model and about how the meteorological and validation data is used.
   - *First of all, a description of Q_bhf is missing, while in Figure 2 it seems to be zero anyway.*

We will add a description of Q_{bhf} and its measurement to the section titled '*4.4.2 Data Collection, Micrometeorological measurements*' as follows:

'Instruments mounted on AWSs are described in Hannah *et al.* (2008). Measured hydrometeorological variables included air temperature and water column temperature (°C), relative humidity (%), wind speed (ms^{-1}), solar radiation and bed heat flux (Wm^{-2}). Meteorological measurements were made ~2 m above the stream surface. The bed heat flux plate and thermistor (for water temperature measurement) were located directly below each AWS. The heat flux plate was buried at 0.05 m depth to avoid radiative and convective errors. The heat flux plate provided aggregated measurements of convective, conductive, advective and radiative heat exchanges between the atmosphere and the riverbed (after Evans et al., 1998; Hannah et al., 2008), and the riverbed and the water column.'

Q_{bhf} was not zero but it was very low/ indiscernible in comparison to the other heat fluxes. It was plotted on Figure 2 to emphasise this.

8. *The net radiation model is described in Eq. 2, but at the end of section 3.4.3 it appears to me that this equation is split up in shortwave and longwave radiation.*

Thank you for bringing this to our attention. We will split Equation 2 into three equations, one for net radiation, one for net shortwave radiation, and one for net longwave radiation. The first five lines of Section '*3.3.2 Net radiation*' will be updated to read as follows:

'A deterministic radiation model developed by Moore *et al.* (2005) and evaluated by Leach and Moore (2010) was used to compute net radiation (Q^*) at the location of each hemispherical image. At each location, net radiation was calculated as:

$Q^* = K^* + L^*$ (Eq. 2)

Where K^* is net shortwave radiation (Eq. 3) and L^* is net longwave radiation (Eq. 4).

$K^* = (1 - \alpha)[D(t)g(t) + s(t)f_v]$ (Eq. 3)

$L^* = [f_v \varepsilon_a + (1 - f_v)\varepsilon_{vt}]\sigma(T_a + 273.2)^4 - \varepsilon_w \sigma(T_w + 273.2)^4$ (Eq. 4)'

We will update Eq. 10 (original submission) appropriately (see response to Point 11)

9. *Eq. 4 is not a Penman style equation, but more a wind function equation. Why not using the full penman equation? The net radiation is determined anyway.*

Eq. 4 is commonly referred to as a Penman-style equation (e.g. Webb and Zhang, 1997; Hannah et al., 2004, 2008; Leach and Moore, 2010; Garner *et al.*, 2014) and has been used successfully in stream energy balance calculations and water temperature modelling (e.g. Webb and Zhang, 1997; Hannah et al., 2004, 2008; Leach and Moore, 2010, 2104; MacDonald *et al.*, 2013; Garner *et al.*, 2014). We will remove the description of Eq. 4 as a 'penman-style' equation but because our chosen method is commonly used and previously published we see no reason to recalculate the turbulent fluxes using an alternative method.

10. *P6452, L12: It is better to use the average velocity between x and x+1. This numerically more robust. The easiest way is to use (u(x)+u(x+1))/2, with u being velocity.*

Thank you for this suggestion. We have recalculated the flow-routing as the Reviewer suggested and also in terms of *x*, which is more accurate and also matches the temperature model. We will change the text as follows:

"The model released water (*i*) from AWS_{open} every hour on each day of the study period. For each parcel of water, the downstream distance (*x*) travelled by the parcel in 15 minutes (Δt) from its location at *x* to *x+1* was calculated as the product of the length of the timestep (i.e. 900 seconds) and the average velocity at Δt and Δt +1. The temperature of the parcel at time t+Δt and location *x+1* was determined by linear interpolation between measurements at 15 minute intervals and between temperature loggers, respectively."

11. *P6452, L24: Similar to above the heat fluxes should have been determined as the mean fluxes between t and t+Δt.*

Again, thank you for this suggestion. The approach used in the original submission has been used successfully by Leach and Moore (2011) and MacDonald *et al.*, (2014a), re-running the model using the model description and structure suggested by the Reviewer, and changing the way we identified our validation data (see Points 10 and Point 16) does improve the water temperature predictions. We will change the text as follows:

"The Lagrangian modelling approach (after Rutherford *et al.*, 2004; Leach and Moore, 2011; MacDonald *et al.*, 2014a) divided the reach into a series of segments (s) bounded by nodes (indexed by i). For each time step, Δ_{900} (s), a water parcel (indexed by j) was released from the upstream boundary; its initial temperature was an observed value. As the water parcel travelled downstream from i towards i+1 the model computed the heat exchange and the net change in stream temperature over each segment as the mean of net energy flux within the segment at time t and time $t+\Delta t$:

$$\frac{dT_w}{dx} = \frac{\left[\left[\begin{matrix} w_{(s)}\left(K^*{}_{(s,t)} + L^*{}_{(s,t)} + Q_{h(s,t)} + Q_{e\,(s,t)} + Q_{bhf\,(s,t)}\right) \\ + w_{(s)}\left(K^*{}_{(s,t+\Delta t)} + L^*{}_{(s,t+\Delta t)} + Q_{h(s,t+\Delta t)} + Q_{e\,(s,t+\Delta t)} + Q_{bhf\,(s,t+\Delta t)}\right)\end{matrix}\right]/2\right]}{C\,F_{(i,t)}}$$

(Eq. 10)

Where $W_{(s)}$ is the mean width of the stream surface (m) in segment s, $K^*{}_{(s,t/\,t+\Delta t)}$, $L^*{}_{(s,t/\,t+\Delta t)}$, $Q_{e\,(s,t/\,t+\Delta t)}$, $Q_{h\,(s,t/\,t+\Delta t)}$ and $Q_{bhf\,(s,t/\,t+\Delta t)}$ are the mean net shortwave, net longwave, latent, sensible and bed heat fluxes within segment s at time t and $t+\Delta t$ (Wm^{-2}). C is the specific heat capacity of water (4.18 x 10^6 Jm^{-3} $°C^{-1}$) and $F_{(i,t)}$ is the discharge (m^3s^{-1}; scaled by catchment area) at node i at time t or $t+\Delta t$.

Water temperature was calculated at 1 m intervals along the reach by integration of Equation 10 in the deSolve package (Soetaert *et al.*, 2010) for R (Version 3.0.2, R Group for Statistical Computing, 2013).

Unsmoothed energy flux data was used for numerical modelling. Incident solar radiation was modelled at 5 m intervals (see section 4.4.3, *Net radiation*); values at 1 m intervals were interpolated linearly. Emitted longwave radiation, latent and sensible heat fluxes were dependent on water temperature. Therefore, these fluxes were calculated at each time step within Equation 23 using values for air temperature, humidity and wind speed calculated by linear interpolation between the two AWSs nearest to the upstream boundary of the segment."

As a consequence of the updated flow-routing and temperature model structures, we will change Fig. 6 to the following:

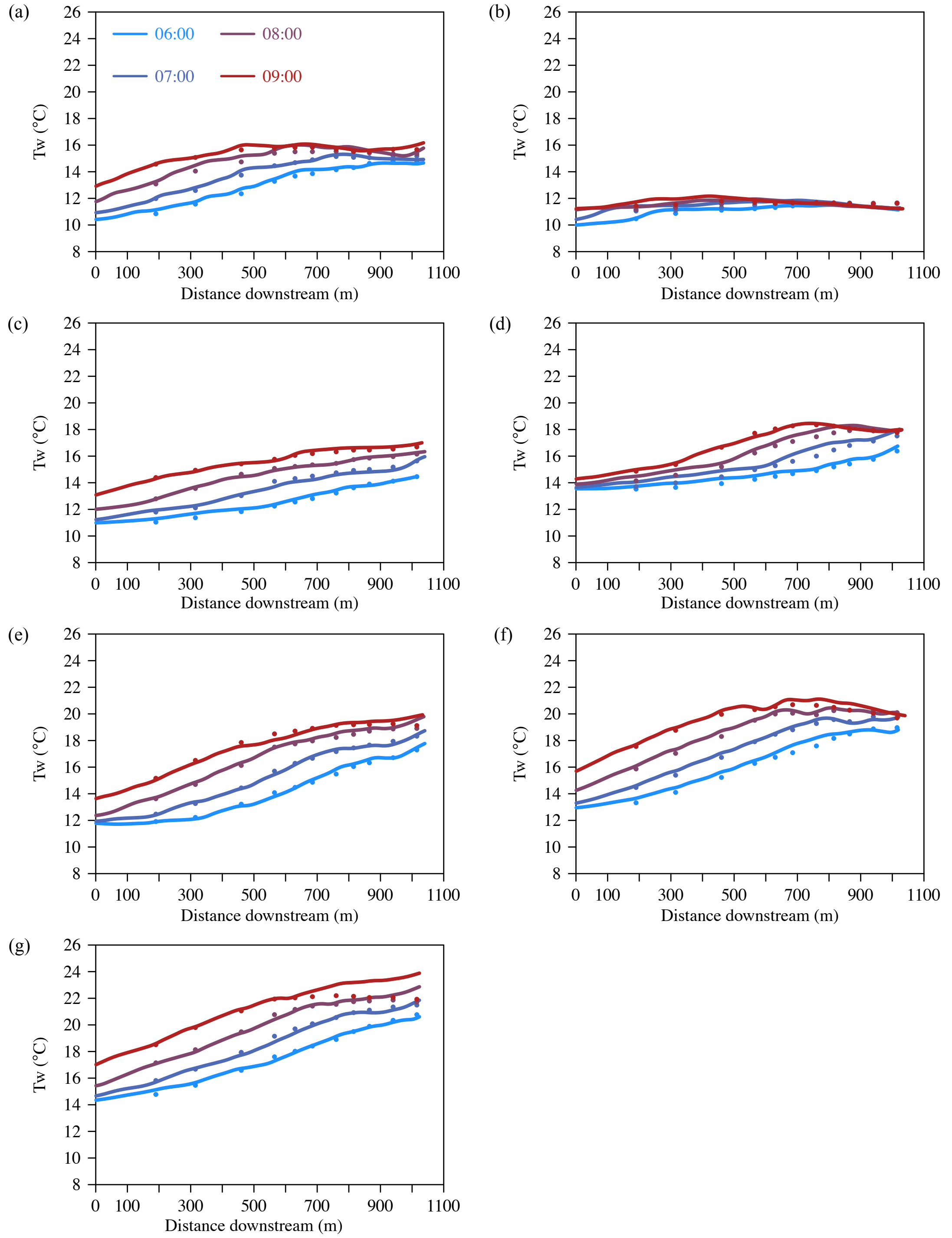

Figure 6. Modelled (solid lines) and observed (points) water temperature of parcels released at 06:00, 07:00, 08:00 and 09:00 GMT on (a) day one (b) day two (c) day three (d) day four (e) day five (f) day six (g) day seven.

12. Are the longwave and turbulent fluxes determined with modelled or observed water temperatures?

Energy fluxes that demonstrate broad spatial and temporal patterns i.e. Figures 2 and 5 use observed values, determined by linear interpolation between the two closest AWSs. We will update the text to state this. Modelled values were used in the stream temperature model (other than those at the upstream boundary), as stated on Page 6453, Lines 8- 11.

13. Be aware that Bowen ration goes to infinity when e_a = e_w (Eq. 8)

Thank you, we are aware of this. However, we have used it successfully in previous studies in this stream (see Hannah *et al.*, 2004; 2008 and Garner *et al.*, 2014) and do not find it to be problematic.

*14. **Smoothing and interpolating***
Apart from the fact that I do not understand how the GAMs work (which degrees of freedom are used, to which data are the models fitted and to which combination of terms is referred to), I do not understand why the spatial canopy data should be smoothed anyway. Since a numerical model is used, this spatial heterogeneity can easily be handled. And, as can be seen in Fig 5a, the smoothing has unwanted effects at the first 150 m (the open part of the stream).

The degrees of freedom were obtained by generalised cross validation within the MGCV library (Wood, 2006). Over-fitting was prevented by setting gamma to 1.4 following Wood (2006).

The statistical models (GAMs) were used to demonstrate broad patterns in canopy density and net energy to the reader, because unsmoothed they are highly variable in space and time. We will state explicitly that unsmoothed data were used in Equation 10 (as numbered in the original manuscript) for numerical modelling (see response to Point 11).

We will clarify our text regarding the GAMS to read:

'Spatial (and temporal) variability in canopy density (and net energy flux) was extremely high. In order to characterise broad patterns in space and time, generalised additive models (GAMs; Hastie and Tibshirani, 1986) were used to provide continuous smoothed estimates of the variability in each dataset. GAMs were fitted in the MGCV package (Wood, 2006; version 1.7-13) for R (R Group for Statistical Computing; version 3.0.2). Degrees of freedom were estimated by MGCV but were limited (gamma= 1.4) to prevent over-fitting (Wood, 2006).

The model fitted to canopy density provided a continuous smoothed estimate of the spatial variability in density from discrete (5 m interval) point measurements determined from Gap Light Analyser outputs. Canopy density was calculated as the percentage of pixels representative of vegetation in each hemispherical image; this percentage was modelled as a smoothed function of distance downstream (i.e. from AWS_{Open}).

The second model provided a continuous smoothed estimate of the spatio-temporal variability in net energy flux estimated at 5 m intervals from the sum of scaled radiative flux (see Sect. 3.3.2), and turbulent and bed heat fluxes calculated from hydrometeorological variables scaled by linear interpolation between the two nearest AWSs. Specifically, net energy was modelled as smoothed functions of: (i) time of day, (ii) day of year, and (iii) distance downstream. The inclusion of three smoothed terms was validated by fitting models using each combination of the three terms and comparing using AIC (Akaike information criterion; Burnham and Anderson, 2002) score (a measure of model fit that balances fit and parsimony) between models.'

15. *The authors also spatially interpolated meteorological data between two AWSs (P6453, L10). This seems completely inappropriate to me, since each of the situations is representative for a certain land use. Thus all numerical grid points in the open field should use data from AWS_open and not an interpolated value between AWS_open and AWS _FUS. This way you get similar effects as in Fig. 5a.*

Meteorological variables measured by AWSs were not representative of unique landuse; two were forested yet meteorological variables measured were very different in magnitude at each. Furthermore, measurements were not only affected by landuse but also surrounding topography, altitude and aspect. Considering all of these factors, spatial interpolation is a reasonable and systematic approach.

16. *On the other hand, the authors do not interpolate data over time, which, in my opinion should be done. Not only for the meteorological data but also for the simulated temperature at x+1: this data should be compared to the interpolated value at $t+\Delta t$, instead of the nearest 15 min (P6452, L14).*

We agree that we should have compared the simulated temperatures to interpolated values of observed *Tw* and thank the Reviewer for bringing this to our attention. We have updated the structure of the flow routing model and the way it identifies the temperature of water parcels and thus the validation data used (see response to Point 11).

17. *P6444, L23: Make clear that longitudinal gradient at a moment in time are considered here.*

Yes, we will.

18. *P6447, L20: According to Fig 1, the gauging station is located just downstream of the point where a tributary comes in. So, how accurate is the discharge used for the model.*

We should have made a similar statement for discharge as we did for velocity on Page 6447, L20- we will address this. As was the case for velocity, discharge scaled by catchment area showed good agreement with gauges made during flow accretion surveys. The inflowing tributary, the Bruntland Burn, has a catchment area of 3 km^2 while the gauging station at Littlemill has a catchment area of 30.3 km^2. The inflowing tributary, the Bruntland Burn, was gauged twice on 01/07/2013 and twice on 04/07/2013 at which times it contributed 9- 11 % of total discharge at Littlemill. Estimating discharge above the confluence of the Girnock and Bruntland via scaling by catchment area yielded a reduction in total discharge of 10%, thus in line with the measured values. Further velocity-area gauges within the reach were accurate to within +/- 5% of scaled discharge at Littlemil. Consequently, we do not believe that the use of discharge measured at this station affected the model results.

19. *P6449, L19- 25: The description of g is a bit fuzzy to me: isn't g(t) simply a function of t, θ, and ψ instead of breaking it up into g* and g(t)?*

The Reviewer is correct that g is a function of t, θ, and ψ but it is split into g* and $g(t)$ because g* is used to calculate the view factor (fv) (Eq 3 in original manuscript) while $g(t)$ is used to calculate net shortwave radiation and net longwave radiation (see equations in response to Point 8). Thus it is necessary to distinguish between g^* and $g(t)$.

20. *P6453, L3: I thought that each water parcel was modelled for each Δt interval.*

No, the model operated in space rather than time. This confusion most probably occurred because we originally calculated the flow routing in time, we have changed this and the flow routing is now calculated in terms of space, x (please see response to Point 11).

21. *P6456, L8: It would be helpful if a couple such lines are added to Figure 6.*

Yes, we will.

22. *P6459, L16- 18: This statement has also been made in Westhoff et al. (2010).*

Thank you, we reiterate that we were not aware of this work (our literature searches were for studies of forested reaches only) and we are more than happy to cite it now that it has been brought to our attention.

23. *P6445, L25: Also give estimates of water depth, discharge and velocity here.*

We will do this for the gauging station at Littlemill.

24. *P6447, L6: Add accuracy and precision of the thermistors.*

We will add the reported accuracy of Campbell 107 thermistors and TinyTags, which is +/- 0.2 °C. We do not think precision is a relevant metric to quote here, since these instruments measure temperature to 3 significant figures but this far exceeds their accuracy.

25. *P6448, L6: I suppose incoming shortwave radiation is meant here? Is rainfall also measured?*

Yes, we do mean incoming shortwave radiation as opposed to only shortwave radiation and will change this. A total of 4.2 mm of rain was measured in the catchment during the study period, we will state this in section '4.1 Prevailing weather conditions'. Thus, rainfall was minimal and was not anticipated to be a significant component of the energy balance (see Hannah *et al.*, 2004; 2008 and Garner *et al.*, 2014).

26. Write the symbol for net radiation also with a subscript (instead of *

This representation of net radiation is used frequently (e.g. Hannah *et al.*, 2004, 2008; Leach and Moore, 2010; 2014, MacDonald *et al.*, 2014b.; Garner *et al.* 2014), so for continuity between publications we see no reason to change this unless the Journal requires it for formatting purposes.

27. P6456, L5: Correct 'reac h'

We will, thank you.

28. Figure 1: I guess the names of the AWS are switched. It is helpful if also landuse is added to the figure.

Thank you for pointing this out. We will alter the naming of the AWSs and add landuse (forested or open moorland) to Figure 1.

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