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# *Interactive comment on* "Constraint of soil moisture on $CO_2$ efflux from tundra lichen, moss, and tussock in Council, Alaska using a hierarchical Bayesian model" *by* Y. Kim et al.

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Point-by-point response to Referee #1's comments

We appreciate the invaluable comments from Reviewer #1 regarding the improvement of this manuscript by careful revision.

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Biogeosciences Discuss., 11, 5902-5939, 2014 (doi:10.5194/bgd-11-5903-2014)

"Constraint of soil moisture on CO2 efflux from tundra lichen, moss, and tussock in Council, Alaska using a hierarchical Bayesian model" by Kim and colleagues

For clarity, see Reviewer #1 (yellow) in the corrected pdf file (bgd-11-5903-2014-R#1.pdf).

âĂČ Response to General Comments

We have addressed the characteristics of the research site, which include limited accessibility and fastidious precipitation events for 2011 and 2012 (see Figure 1). Further, it was difficult to measure CO2 efflux due to unstable, heavy precipitation events during the growing season of 2012. With this in mind, we had to conduct one or two CO2 efflux-measurements under clear sky for the observation period. We used the HB model to overcome limited efflux measurements for the observation month (Nashina et al., 2009; 2012).

As such, my colleagues and I have carefully revised the manuscript as suggested by Reviewer #1's comments.

We further deleted Figures 3 and 4 and added supplementary material, as suggested by Reviewer #1.

Response to Specific Comments

Abstract L12-18: soil moisture causes 1.4-fold differences in CO2 efflux between two growing season, yet temperature "as the most important parameters in regulating CO2 efflux". More clarifications are needed here, maybe specify the importance of moisture and temperature on different temporal scales? That moisture contributes to interannual CO2 efflux more and that temperature controls seasonal variation?

»> Yes, while temperature controls the seasonal variation of CO2 efflux, soil moisture contributes to interannual variation of CO2 efflux, as pointed out by Reviewer #1. »> We rewrote P5904 L18-19 of the Abstract, as follows. This reveals that soil temperature regulates the seasonal variation of CO2 efflux, and that soil moisture contributes to the interannual variation of CO2 efflux for the two growing seasons in question.

Abstract L24: the use of "period" as flux unit needs more clarification, do you mean



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growing season as a period? If so, then period-1 may be omitted. How is the proportion of annual rates of the whole western tundra ecosystem estimated? A brief sentence in the abstract explaining this would be preferred.

»> We removed the unit and added explanation in P5904 L24 of the Abstract and P5920 L16 as follows.

P5904 L24: Estimated growing season CO2 emission rate ranged from 0.86 MgCO2 period-1 in 2012 to 1.20 MgCO2 period-1 in 2011, within a 40 m × 40 m plot, corresponding to 86 % and 80 % of annual CO2 emission rates within the Alaska western tundra ecosystem, as estimated by the temperature dependence of CO2 efflux. P5920 L16: That is, the simulated CO2 emission rates were 0.86-1.20 MgCO2 period-1 within a 40 m × 40 m plot during the growing seasons of 2012 and 2011, respectively. »> Regarding the calculation, we simply multiplied CO2 emissions (539 and 742 gCO2 m-2 period-1) by 1400 m2 (within a 40 m × 40 m plot). Further, annual CO2 emission of the whole western tundra ecosystem can be estimated using Eq (2), as written in P5920 L10.

P5906 L16-17: “If spatial distribution is . . . cause estimation bias”. The sentence may be further clarified. Spatial distribution of what? Do you mean the spatially clumped monthly CO2 efflux or the repeatedly measured (time series) of CO2 efflux? How is the ensemble average defined here? Expand this sentence into several and provide more details should make the message clearer.

»> We deleted this sentence because it has no particular meaning for this study.

P5910 L15-21: “fp is a linear predictor that has three parameters”, but only ðİŻ¡0 appeared in eqn 6, where is ðİŻ¡1 and ðİŻ¡ 2? Also, ðİŻ¡ is not defined in eqn7.

»> We rewrote section 2.3 for the ðİŻ¡0. Parameters ðİŻ¡1 and ðİŻ¡2 do not exist for this manuscript.

P5911 L3: Is Qtem the same as Q10 in eqn3? Or should “tem” be “ten”?



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»> We changed Qtem to Q10 in Eq (2).

P5911 L5: eqn 8, WFPS has not been defined in previous text.

»> WFPS does not exist for this manuscript.

P5911-5912: how is the probability density function of hyperpriors obtained? For example, what is the basis for assuming the same variance of vegetation and year random effects? The posterior parameter distribution can be very sensitive to priors and the resulting conditional distributions. The hyperpriors for ðİŻ¡0, ðİŻ¡1 and ðİŻ¡2 are missing from the list and eqn 13. Should not eqn 13 be ". . .Normal(F| u,ðİŻ£)×p(u, ðİŻ£|ðİŻ¡, a,b,c. . ..)×p(ðİŻ¡)×p(a)×. ."

»> We have added explanation regarding how to get priors as follows. We set priors for $\sigma$vege2 and $\sigma$year2 to be vague, with a large enough value for the actual observed CO2 efflux in this study. »> We are very sorry for the confusion. The authors misunderstood model descriptions in Biogeosciences discussion. The four comments regarding the HB above were revised in this version, as suggested. We appreciate your helpful comments. The correct model description is as follows, 2.3 Description of Hierarchical Bayesian (HB) model In a HB model, in order to evaluate the relationship between CO2 efflux and environmental variables, we modeled observed CO2 efflux using a HB model with four explanatory variables: soil temperature (ST), soil moisture (SM), vegetation types (Vege), and thaw depth (THAW). First, CO2 efflux (FCO2) was assumed as normally distributed with mean parameter ($\mu$flux) and variance parameter (ðİIJŐ): F_(ãĂŰCOãĂŮ_2 ) âĹijnormal($\mu$_flux,$\sigma$ˆ2). (4) The scale parameter ($\mu$flux) was determined from the following equation: $\mu$_flux=f_P f_ST f_SM f_THAW, (5) where fP represents the function of CO2 efflux potential, and fT and fSM are limiting response functions ranging from 0 to 1. fP was defined as follows: f_P=$\beta$_0+ ãĂŰVegeãĂŮ_[k] + ãĂŰYearãĂŮ_[l] + ãĂŰPosiãĂŮ_[ij] . (6) fP is a linear predictor with intercept ('$\beta$0') and three random effects (Vege, Year, and Posi). The Posi term represents a spatial random effect from a conditional autoregressive model (CAR) proposed by



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Besag et al. (1991). Temperature (fT) is a modified van't Hoff equation as follows: f_ST=eˆ((ST-ãĂŰSTãĂŮ_ref)/10 logâĄą(Q_10)), (7) where fST is the temperature response function, which varies from 0 to 1. The explanatory variable of this function, represented by ST and STref, is a constant, set at 25 °C in this study. The temperature sensitivity parameter is Q10. The soil moisture liming function (fSM) is defined as follows: f_SM=((SM-a)/(b-a))ˆa ((SM-c)/(b-c))ˆ((-d(b-c))/((b-a))), (8) where the soil moisture response function is fSM, ranging from 0 to 1, and is the same as the temperature response function (Hashimoto et al., 2010). SM is the explanatory variable of this function, and a, b, c, and d are parameters for determining the shape of the soil moisture function. The function has a convex shape, and values range from 0 to 1. Parameters a and c are the minimum and maximum values of SM, respectively (i.e., g(a) = g(c) = 0). Parameter b, which ranges between a and c, is the optimum parameter (i.e., g(b) = 1). Parameter d controls the curvature of the function, though the three other parameters also affect the shape. This function was adopted from the DAYCENT model (Parton et al., 1996; Del Grosso et al., 2000). fTHAW is a function of thaw depth. We modeled this as follows: f_THAW=1/(1 + eˆ(k-r THAW) ), (9) where the thaw depth function also ranges from 0 to 1. THAW is the explanatory variable of this function, and k and r are the parameters. We assumed CO2 efflux to monotonically increase with increase in thaw depth (depth of active layer); however, this increase is not simply proportional with thaw depth due to carbon depth distribution. Finally, we modeled priors of each parameter. For vegetation, we incorporated random effects as follows: ãĂŰVegeãĂŮ_k âĹijnormal(0,$\sigma$_vege) and (10) ãĂŰYearãĂŮ_l âĹijnormal(0,$\sigma$_year). (11) For spatial explicit random effect, we used a CAR model (Besag et al., 1991) as follow: ãĂŰPosiãĂŮ_il âĹijnormal(b_ij,$\sigma$_(ãĂŰposiãĂŮ_ij )/n) b_il âĹij1/n_ij $\sum$_$(m = 1)(neighbors(ij))b_m, where nij is the number of neighbors for neighborhood ij. For priors, we defined as follows: \beta$_0 âĹijnormal(0,1000), Q_10 âĹijuniform(1,10), a âĹijnuniform(-2,0), b âĹijuniform(0.1,0.5), c âĹijuniform(1,3), d âĹijuniform(0.01,10), k âĹijuniform(0,10), r âĹijuniform(0,1), $\sigma$ˆ2 âĹijuniform(0,100), $\sigma$_vegeˆ2 âĹijuniform(0,100), and $\sigma$_yearˆ2 âĹijuniform(0,100), (12) For $\beta$0, we used a normal distribution with



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mean 0 and a very large variance. Priors regarding the soil moisture function (a, b, c, d) are based on Hashimoto et al. (2012). We set priors for $\sigma$vege2 and $\sigma$year2 to be vague, with a large enough value for the actual observed CO2 efflux in this study. Joint posterior probability was described as follows: p($\theta$âŤĆdata)âĹİ$\prod Normal(F_(CO_2)|\mu$,$\beta$_(o,10),a,b,c,d,k,r,$\sigma$_1,ãĂŮ $\sigma$_vege,$\sigma$_year,$\sigma$_(posi )) $\times$ p($\beta$_o)$\times$ p(Q_10)$\times$ p(a)$\times$ p(b)$\times$ p(c)$\times$ p(d) $\times$ p(k)$\times$ p(r)$\times$ p($\sigma$_1)$\times$ p($\sigma$_vege)$\times$ p($\sigma$_year)$\times$ p($\sigma$_(posi )), (13) where p($\theta$) denotes priors. For this model, we used MCMC methods implemented with Bayesian inference, using Gibbs sampling software WinBUGS (WinBUGS, version 1.4.3; D. Spiegelhalter et al., 2007, available at http://www.mrc-bsu.ac.uk/bugs). We used the Gelman-Rubin convergence diagnostic as an index. For the model, we ran the Gibbs sampler for 20,000 iterations, for three chains, with a thinning interval of 10 iterations. We discarded the first 10,000 iterations as burn-in, and used the remaining iterations to calculate posterior estimates. R was used to call JAGS/WinBUGS and calculate the statistics in R.

P5912: It would be good to have a graph showing the convergence of the Gibbs sampler results. Maybe put in the supplementary.

»> We added convergence plots in the supplemental material as follows.

Supplementary material: Convergence plot of all HB model parameters

Fig 10: why did not soil moisture drop rapidly in Sep 2012 when temperature dropped to zero as oppose to 2011?

»> I fully understand the concern. Soil moisture dropped rapidly in September 2012, when soil temperature dropped below zero. However, if we measured soil temperature after mid-September 2011, soil moisture would show a similar drop. Because of the weakness of the solar power supply in the late growing season, we could measure only growing season soil temperature and moisture for 2011 and 2012.

»> Contrary to Sep 2011, air temperature in Sep 2012 dropped rapidly, as shown in



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Figure 1. These data came from the Western Regional Climate Center of the National Weather Service, Alaska. This is not in-situ data; however, in-situ air temperature in mid-Sep 2012 did read below zero, despite the short period of observation (ca. 2-month) caused by trouble from the power supply, as shown in the following Figure.

»> Recently, we solved these mechanical problems by installing sensors and loggers for soil temperature and moisture, obtaining year-round data since 2012.

Figure. In-situ air temperature data in Council, Alaska from mid-July to mid-September, 2012.

P5918 L25: the effect of thaw depth shown in fig 5c is not quite similar to the limiting function used (assumed) in eqn 8 (fig7c). More discussion of the interacting effects of thaw depth and soil moisture may be needed, as it is likely that the thaw depth effect is masked by moisture.

»> In the view of the observation, we expected the increasing CO2 efflux as thaw depth deepens; however, the expectation was deflected. Further, there were different meteorological patterns between years, which may be due to effects from heavy rainfall in 2012. Some relationship between thaw depth and moisture may be represented if thaw depth was regulated by the masking effect of soil moisture. However, we could not find any relationship between the two in our simple empirical model. In the HB model, by assuming a possible relationship between flux and thaw depth and under constraint of parameter estimation from priors, we could estimate the positive (though weakly so, in the actual range of thaw depth during measurement period) effect of THAW depth and non-linear relationship of soil moisture respectively.

P5920 L10: So the annual estimation of CO2 emission from tundra ecosystem is based on eqn 2. Did you use the HB results for parameters in this extrapolation?

I would recommend re-estimate those parameters in eqn2 as that way the new parameters can compensate model structural insufficiencies (compare with HB model) to



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some extent.

»> We recalculated and corrected annual $CO_2$ emission for 2011 and 2012 using the parameters 827 and 609 $gCO_2$ $m^{-2}$ $year^{-1}$, respectively, in P5920 L10, as suggested by Reviewer #1.

Table 3: some parameters showed quite a posterior 95% CI, especially soil moisture related parameters. I am wondering if a simpler moisture effect function (eqn8) can be used or maybe compared with the current one to see if there is an overparameterization issue with the complicated model with fewer degrees of freedom.

There seems to be too many figures in the manuscript, some of them deliver limited message (neither closely related to the main message of the manuscript nor receive ample discussion), such as fig3 and 4. I suggest replace them with other indepth results from HB model analysis if any or just delete or put in supplementary information.

»> We deleted Figures 3 and 4 and added the convergence plot for all HB model parameters, as suggested by Reviewer #1.

Thank you for this suggestion. We have conducted two types of soil moisture function for the HB model and evaluated DIC (deviance information criteria) in each model as follows: DIC 1) This study (revised one) 2463.9

$f_{SM}=((SM-a)/(b-a))^a ((SM-c)/(b-c))^{((-d(b-c))/((b-a)))}$

2) Simpler function 2505.3

$f_{SM}=e^{((-ep(1-SM/Wopt)^2))}$

In view of model selection using criteria, lower DIC means higher predictability for the fitted model, which is judged by a balance of performance and model complexity, owing to parameter parsimony. These results suggest that the current model still performs well, compared to the model with two parameters for soil moisture function. Therefore, we continue to use the current model in the revised manuscript. However, we have huge questions for possible models regarding non-linear function (including linear models). As a result, we cannot compare possible model combinations.

Supplementary material is unavailable following the link in the manuscript.

»> We have attached supplementary material regarding the convergence plot for all HB model parameters, as suggested by Reviewer #1

Technical issues:

P5905-L27: I understand the authors use "parameter" to refer to environmental factors controlling CO2 efflux, but technically parameter refers to a time-invariant subject that characterizes the modeling system, and soil temperature in this context, is regarded as forcing of the modeling system whereas how we characterize the "effect" of temperature on soil CO2 efflux can be a parameter. I recommend the authors change the "parameter" to "factors" or "environmental variable" as such throughout the manuscript to clarify such mixed usage.

»> We rewrote 'parameters' relating to the HB model, and 'factors' for other cases, as suggested by Reviewer #1.

P5913 L10: "Annual average" to "Annual growing season average"

»> We changed 'annual average' to 'annual growing season average,' as suggested by Reviewer #1.

Table 3: "fro" to "of". Some parameters in this list do not match those in the text. »> We rewrote and corrected them, as suggested by Reviewer #1.

Please also note the supplement to this comment:
http://www.biogeosciences-discuss.net/11/C4282/2014/bgd-11-C4282-2014-supplement.pdf

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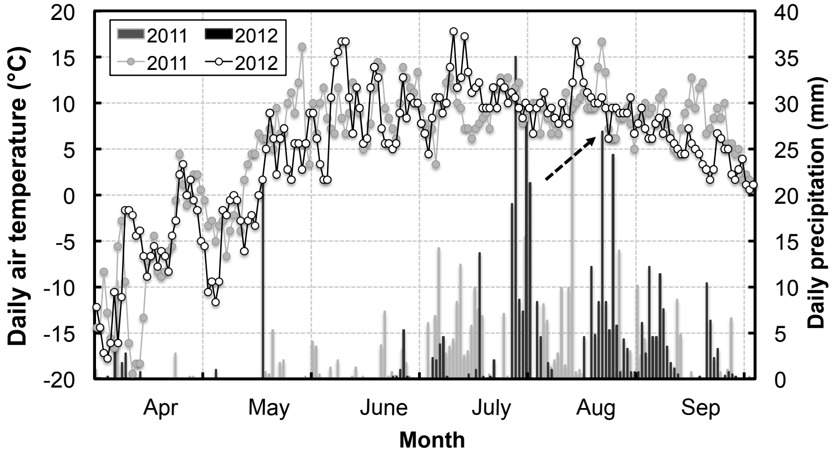


Figure 1

**Fig. 1.** Revised Figures and Tables



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