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Hydrology and Earth System Sciences Discussions

Interactive comment on "Impacts of soil-aquifer heat and water fluxes on simulated global climate" *by* N. Y. Krakauer et al.

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We thank the reviewers for their careful readings, and appreciate the opportunity to submit a revised and improved version of our paper. Our responses to the points raised are as follows:

1 Review 1 (Bierkens):

a) *Page 1189, line 12: here it is said that bedrock fractions were changed? For what reason? Explain in the text.*

We now discuss this more explicitly: "These modifications to bedrock function and root depth allow vegetation greater access to deeper soil moisture, and permit more extensive interaction between the soil and the aquifer layer. Multiple studies have identified access to deeper soil moisture as an important aspect of water uptake by plants during dry periods; deep roots have been found to take up substantial amounts of water from deep, wet soil when shallow layers dry out even if their contribution to root biomass is small (Jackson et al., 2000; Feddes et al, 2001; Lee et al, 2005; El Maayar et al., 2009)."

b) *Page 1191: I am a bit confused about equation (3) and (4). Why would one take the gradient over the fixed value dz_n and not over z_n - z_delta. This way, if the groundwater level is very deep, the percolation flux becomes very large, larger than K_N, which is not logical. I expect it to become equal to K_N for very deep water tables and h_n not too negative. Please explain.*

We now address this in the Discussion: "Similarly, assuming a uniform water potential within the aquifer layer (equivalent to infinite hydraulic conductivity within the layer), as we did here, will tend to lead to water fluxes that are higher than would be expected in reality for the same mean water contents in the aquifer and soil layers. Thus, the effect we find on climate of the soil-aquifer water flux can also be regarded as an upper limit."

c) *Page 1191, line 16: please explain how flows were restricted to avoid numerical instabilities.*

We now elaborate on this: "specifically, the aquifer water content is not allowed to decline by more than half at each timestep"

d) *Page 1192: line 3: why 1850 conditions? Why not fix the CO2 on average 1980-2010 for instance?*

We based our simulation on preindustrial conditions for approximate equilibrium of the climate with the applied forcings, since long integrations were needed for the aquifer water content to reach an approximate steady state. By contrast, the climate of recent years is out of balance with the current greenhouse gas forcing. We state that "our runs had artificially low interannual variability in climate forcing and sea-surface boundary conditions (SSTs kept at climatology, constant greenhouse gas levels); a next step will be to examine how climate persistence changes in the presence of more variability, as well as in the presence of changing climate forcings such as greenhouse gas levels"

e) *Page 1192: line 19-20: provide more details on how this interpolation is done.*

We now give more detail: "In the Aquifer and WaterOnly runs, trends in the aquifer water content were extrapolated several times by fitting exponential decay functions to the time series and then re-initializing runs with the extrapolated water water contents in an attempt to speed up convergence."

f) *Page 1195, line 22-25. When discussing the heat flux: I wonder how important how important geothermal heat flux is, especially in Nordic areas with a permafrost cover. In other words, should instead of a zero flux lower boundary a fixed non-zero flux or fixed temperature at the lower aquifer boundary be more appropriate?*

We added a paragraph to address this: "As previously in ModelE and in other climate models (Nicolsky et al., 2007), geothermal heat flow was neglected in assuming no-flux bottom boundary conditions. Adding geothermal heat flow would be expected to warm our aquifer layer by up to 1 K, taking a typical continental geotherm of 25 K / km (Mock et al., 1997). This heat flow may be more important over multi-millennium simulations, particularly for representing conditions at the bottom of ice sheets (Pollard et al., 2005)."

2 Review 2:

a) *In several places, the authors say that the soil temperature changed in this way or that, but they do not clearly define what they mean. Are they showing soil temperature of the aquifer, the bottom of the original soil column, the surface, or integrated. I suspect integrated, but over what depth?*

We now specify that "Soil temperature is given averaged across the soil layers (to 3.5 m depth), and soil water content is similarly summed across the soil layers."

b) *P. 1187, line 28. "The separation $\cdots$ is conceptually difficult". This is a strange way of putting it. I would use something like unrealistic instead of difficult.*

Agreed. We rephrased this.

c) *Validation — There is little mention of validation of the aquifer parameterization. I realize that this may be difficult to impossible, but I think some additional discussion would be useful. You mention GRACE data has been used in other studies to evaluate models with and without aquifers. Why didn't you test against GRACE here? Are there any other datasets, either datasets that already or exist or more likely datasets that don't exist at present, but which if collected would help inform modelers about realistic aquifer representations? Soil temperature measurements, for example.*

We have expanded our discussion of validation strategies to address this more fully: "Available water table and streamflow data along with total water storage changes from the GRACE satellites may also be useful for calibration of parameters in GCM simple aquifer representations, using one of several already demonstrated approaches (Lo et al., 2010; Werth and Guentner, 2010; Becker et al., 2011; Vergnes and Decharme, 2012), particularly when the GCM runs include more realistic climate variability (compared to the climatological sea surface temperatures and greenhouse gas concentrations used in the runs reported here, which were intended to represent an idealized, stable preindustrial climate). Soil data obtained at different depths, now being aggregated in the International Global Soil Moisture Network (ISMN, which holds soil temperature as well as water content data) (Dorigo et al., 2011), may also be useful in validating the modeled effects of water and heat fluxes on the soil temperature and moisture profiles and on their temporal correlation patterns, though meaningfully comparing global model outputs to in situ measurements of soil properties remains a challenge (Seneviratne et al., 2010; Luo et al., 2012). Borehole temperature measurements may also be useful in validating model heat fluxes over depths up to hundreds of meters under conditions of climate change (Beltrami et al., 2006)."

d) *Table 3 shows autocorrelations for 1-yr lags. What about shorter lags? The autocorrelations are pretty small at one year, which is common for land models. Bigger impacts might be seen for autocorrelations for monthly or seasonal lags.*

To illustrate how the impact of soil-aquifer fluxes on autocorrelation varies with lag time, we now also present and discuss lags at 3 and 48 months as well as 12 months.

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