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A general framework for understanding the response of the water cycle to global warming over land and ocean

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Response to Comments by Referee (Prof. Sivapalan)

Referee comments in Italics

I enjoyed reading the paper: some time ago eminent physicist S. Chandrasekhar published a voluminous book titled "Principia Mathematica for the Common Reader", which was still over my head (in spite of written in English as opposed to Newton's Latin). This paper could be termed "climate change for the common hydrologist": just like some eminent climatologists are wont to do (e.g., Ramanathan), it aims to capture the bare essentials so the common hydrologist reader can get to the bare essentials. I want to add a few more comments and suggestions that the authors can make this even better.

We thank the reviewer for the positive comments.

(1) I felt that the authors went too far in simplifying to the point some parts of the text seem rather cryptic. In view of the potential educational value of this paper, it may be more useful to make this a bit more clear. I give an example: the sentence "... the atmospheric humidity is projected to increase at the Clausius-Clayperon (CC) value of around 7%/K". A similar statement is made later about P, which was clear, but I was confused by the CC reference here.

We were unsure of the point being made. We think it refers to the spelling mistake (should be Clapeyron) and we can fix that.

(2) I can follow the arguments on the authors' interpretation and clarification of the results of Held and Soden. However I am unclear about the take-home message from this. Is the message meant for climate scientists or for hydrologists? As a hydrologist, I don't know what to make of this for my work - may be the authors can clarify.

The message is for both atmospheric scientists and for hydrologists. In particular, one often hears the statement in the press or even in scientific papers that the wet get wetter and dry get drier. However, as we note, in terms of P-E at least, climate models ijn the CMIP3 archive do not actually project this at the local scales that matter for impacts and for management. Those local scales are also of primary interest for hydrologists. We can perhaps spell that out a little better in a revision.

(3) I will say something similar about the authors' findings about Budyko. It is clearly reassuring that climate models "on average" satisfy the Budyko theory of annual water balance partitioning. Is this the take home message? I agree that this is important: some 20 years ago during the PILPS experiment (inter-comparison of land surface parameterizations) that climate models did not satisfy Budyko, which was a major concern. In spite of the good result, I remain curious - how did this happen? Unlike the comments of one of the reviewers,

this is not just a matter of balancing water and energy: it is about co-evolution of climate, soils, vegetation etc. Any insights by the authors would be very valuable.

(4) One more query on the Budyko: again, what is the take home message? Is it that climate models are now able to satisfy Budyko "on average"? Of course they should, if they are to be used with confidence? I am wondering if there is a deeper message here.

These (3 & 4) are good questions. We were aware of earlier results with PILPS and we admit to being (pleasantly) surprised by the finding that the model ensemble average does follow the standard Budyko curve. As the reviewer implies, that result should give a clear indication to hydrologists that the climate models are not without some skill in terms of the partitioning of water and heat at the surface. As to deeper insights - we really do not know why. We assume that the models strictly enforce mass and energy closure schemes over the land surface. That would explain the close adherence to the water and energy limits but it is a little more difficult to explain why the model ensemble average gets the apparent curvature correct as well. This is particularly interesting since we know from work by Prof Graeme Stephens and others that the rainfall dynamics are not well simulated by climate models.

(5) Compared to these interpretations (above), to me the more interesting conclusion of climate models is for a global increase of P by around 1-3 %/K. Isn't this the essence of the "response of the water cycle to global warming" (from the title of the paper). I was expecting that the paper would also address this point, as this would be of a lot of value to hydrologists. I looked for discussion of this and did not find it (or did I miss it). I felt that the second part of the paper skirted this issue, but I could not make the connection. May be the authors can clarify.

Perhaps we need to rewrite this. As we noted, the response of global P is equal to the response of global E. In the second half of the paper we decomposed the response of global E in terms of projected changes in the surface energy balance over the globe and separately for both land and ocean.

(6) In conclusion, it may be good if the paper can be organized so that clear take-home messages that hydrologists can use. These are already there probably, and only need to be brought out more clearly.

Perhaps we could add a summary section that makes the key points as follows:

(a) Climate models do not project that the wet get wetter and dry get drier at local scales when wetness is measured as P-E.
(b) Climate models are skilful in terms of the long term mean annual partitioning of heat and water at the surface because the ensemble average reproduces the Budyko curve. However, research elsewhere has also shown that the models are not as yet useful at local scales in terms of P. In summary, the partitioning of P is in accord with hydrologic experience but the value of P is uncertain.
(c) With respect to CO_2 forcing, the net response is a very simple one. In particular, the incoming longwave irradiance increases and most of that is simply sent back to the atmosphere as an increase in outgoing longwave irradiance and hence an increase in surface temperature. Other projected changes in the surface energy balance are very small and probably would be difficult to even measure.
(d) Any enhancement of the hydrologic cycle will limit the increase in surface temperature (and vice-versa). In particular the change in global P and surface temperature are not independent.

Michael L. Roderick, Fubao Sun, Wee Ho Lim, Graham D. Farquhar, 12/3/2014