Manuscript Details:

Hydrol. Earth Syst. Sci. Discuss., 10, 15263–15294, 2013

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

Authors:
M. L. Roderick, F. Sun, W.H. Lim, G.D. Farquhar

Response to Referee Comments by Dr van der Hurk

Referee comments in Italics

1. *This manuscript describes in a clear and easy to follow manner the effect of green-house warming on the global balance of P and E, elaborating on earlier work by Held and Soden (2006). It shows that the zonally averaged estimates of d(P-E) do not hold at the grid box level and not over land, and present an alternative Budyko-based framework for this. It also illustrates the small role of changes in surface evaporation, and the dominance of longwave cooling at the surface. It reverts the (public) rationale that elevated temperatures lead to acceleration of the hydrological cycle: had surface evaporation increased more, the surface warming would have been correspondingly less.*

We thank the reviewer for the positive comments.

2. *The main question that then remains unanswered is the physical explanation of the current partitioning of dLin over dLout and dE: why is x in Eq 10 equal to 0.24? It probably is related to the notion that relative humidity changes relatively little, but it does not shed light on why this is the case. Do the authors have evidence for this?*

Very good point.

We did try but we were unable to find a definitive underlying physical reason for that finding. We agree that the so-called water vapour feedback is likely to be central but in the absence of a physical explanation the only option is to leave it as a model result that requires future explanation.

3. *The paper reads very well (very suitable for teaching at MSc/PhD level) and is certainly suitable for publication, apart from a number of minor comments:*

We thank the reviewer for the positive comments.

4. *p 15270: the number of references to the Budyko framework (19) is a bit overdone, I would say.*

When we originally asked an experienced atmospheric sciences colleague to comment on the work they responded by stating something along the lines of … "the Budyko thing must be pretty good because it agreed with climate models". In fact the reality is the other way round with the test being whether the climate models were consistent with hydrologic understanding embodied in the Budyko curve. With that background we wanted to ensure that readers not familiar with Hydrologic applications of the Budyko curve could peruse a variety of key literature to see the generality of the approach.

In response we have removed two references from the list and note that we would greatly prefer to keep the remainder as they represent some of the key works that readers could follow up.

5. *Eq 1: can you give some indication of the typical value of n?*

The value of n that best reproduces the original Budyko curve is 1.9 (Donohue, Roderick, McVicar, 2011 J Hydrology 406: 234-244). We used n = 1.8 in Figure 2ef as noted in the caption. In previous work we have calculated values of n using long term catchment data in Australia and found values ranging from 0.6 to 3.6 (op cit). That range has also been found in Chinese catchments.

We modified the text following Eqn 1 to address the questions raised.

6. *p 15271, second para: the fact that the models obey the Budyko framework so well is not very surprising, as both are based on conservation of energy and water. A model data set can be expected to better comply with this framework than an observational data set where energy and water balance conservation are normally quite problematic*

As noted by another reviewer (Sivapalan), it is not so straightforward. While the asymptotes may be straightforward the approaches to them are not. The curvature in the Budyko curve is an emergent relation and depends on many things (e.g. water, energy, soil-vegetation, etc.). No change was made.

7. *p 15272, last sentence: add a statement that the framework is not suitable for the cryosphere since additional long-term mass balance terms (storage in snow/ice packs) violate the balance assumptions*

We modified the sentence as per the reviewer's suggestion.

Original sentence reads:

The Budyko framework is not intended for use in the cryosphere and we limit the calculations to the latitudinal range 60S to 60N.

We replaced that sentence with:

The Budyko framework is not intended for use in the cryosphere since additional long-term mass balance terms (snow/ice) violate the mass balance assumptions. We limit the calculations to the latitudinal range 60S to 60N.

8. *p 15273: the 82% explained variance shown in fig 4 is actually a bit low, since all terms in eq 3 come from the same model archive. The missing terms that explain this limited fraction of explained variance are the (ignored) changes in n and the covariance terms, is that right?*

Yes, that is correct. In addition, the explained variance would have increased if we used the best fit value for n (=1.5) instead of the recommended default value for n (= 1.8).

9. *p 15279, L15: add the word "averaged" before "model ensemble", as the word "en-semble" often points at a large collection of model data*

Good point. We also located several other instances of the same problem in the text (e.g., P15266, line 18; P15270, line 8 & 18; P15271, line 13; P15274, line 10; P15275, line 7 & 13; P15277, line 18; P15278, line 18; P15280, line 18; P15279, line 21).

We have fixed all instances of this problem throughout the text.

10. *it is a coincidence that the fractional changes in dP and dE over land (5.3 and 3.7) add up to the fractional change in d(P-E) (9%). It may be helpful to make this notion*

We did not notice that originally, but yes, it is a (peculiar numerical) coincidence (in Table 1).

Response to Comments by Referee (Prof. Savenije)

Referee comments in Italics

This is a very interesting and well prepared paper, which clearly shows that interpretation of climate change effects only make sense if we distinguish between land and ocean, where the land is moisture constrained whereas the ocean is not. The Budyko framework is a very useful way to analyse the sensitivity of the hydrological fluxes to changes in energy and precipitation input. This paper is brilliant in its simplicity, and I very much welcome a resubmission.

We thank the reviewer for the positive comments.

There are two sets of comments that I would like to make. The first set refers to the correct use of units, the second to an additional feature that becomes clear if a different functional form of the Budyko curve is chosen.

1a. In the paper the evaporation is sometimes expressed as a volumetric flux per unit area (mm year) and sometimes as an energy flux per unit area (W m-2). In the latter case the evaporative flux is symbolized by LE. Although the paper doesn't say so, the convention for L (Specific latent heat) is the energy (heat) required to evaporate 1 kg of water (=2.45 kJ/g). It then still requires multiplication with the density to become a volumetric flux per unit area. So the equation should use ρLE for LE (if E is expressed in a volume flux per unit area, as the paper does). Unless of course L has the unit J m-3. So preferably include the density, or explain that L includes the density. This also applies to all the places where LE or LE are used (eqs. 5, 6, 7, 8, 11, 12; p15275, L10, L19; p15276, L1, L5; p15277, L8 and caption of Table 2).

Good point. We use common hydrologic units (volume per area per time) but we agree that it is dimensionally inconsistent with the equations we use. The equations themselves are dimensionally correct – it is in the tables and in the Budyko analysis where we make this dimensional error.

We have now added a new paragraph to section 2 explaining the unit convention adopted.

1b. Another mistake often made is that G in eq.(5) is not the storage of heat, but the storage increase over time. It is the temporal derivative of the heat storage and not the storage itself, as is suggested on p15274, L7 and in the caption of Table 2. This may seem like nitpicking, but in HESS we want to be precise in the correct use of units and dimensions. Of course one might say that the term storage means the process of storing, but this is not what in hydrology is the convention. The storage of water is the water stored. The term dS/dt in the water balance means the temporal change of storage and not the storage; similarly G is the temporal change of heat stored in the earth and not the amount stored. The temporal derivative of the storage is the process of storing or depleting. Maybe a way out is to replace the term 'heat storage' into 'the process of heat storage', or to replace it with 'heating up'.

Good point. We agree. We have refined our description and now use change in enthalpy for *G* throughout.

2. The authors prefer to use a Budyko curve of the type presented in (1). A simpler form of the Budyko curve is

$$\frac{E}{P} = \left(1 - \exp\left(-\frac{E_0}{P}\right)\right)$$

This exponential equation may have the disadvantage that it does not have the additional parameter n, which allows additional tuning, but the authors don't make use of n anyway. An advantage of this equation is that it links to the probability distribution of rainfall (see: De Groen and Savenije, 2006, and Gerrits et al., 2009), and hence has some physical reasoning behind it. A further advantage of this equation is that ε_0 *and* ε_p *have physical meaning. It can be shown that* ε_0 *equals the runoff coefficient:*

$$\varepsilon_o = \frac{P - E}{P} = \frac{Q}{P} = C_R$$

This follows simply from partial differentiation of the exponential Budyko curve. In fact, Figure 3b shows the global distribution of the runoff coefficient. If the colour scale is changed to a maximum of 1.0 (now it is scaled at a maximum of $16*10^{-1}=1.6$*, which is a physically impossible number), then we recognise immediately the distribution of the runoff coefficient over the world. I think using the exponential definition of the Budyko curve makes the paper even more transparent. In addition it can be shown that:*

$$\varepsilon_p = 1 - \frac{E}{P}\left(1 - \frac{E_0}{E}C_R\right) = 1 - \frac{E}{P} + \frac{E_0}{P}C_R = \left(1 + \frac{E_0}{P}\right)C_R$$

So ε_p *is proportional to the runoff coefficient and is strengthened by the aridity index. These expressions can also be obtained directly by derivation of the exponential Budyko curve:*

$$\mathrm{d}Q = \frac{\partial Q}{\partial P}\mathrm{d}P + \frac{\partial Q}{\partial E_0}\mathrm{d}E_0$$

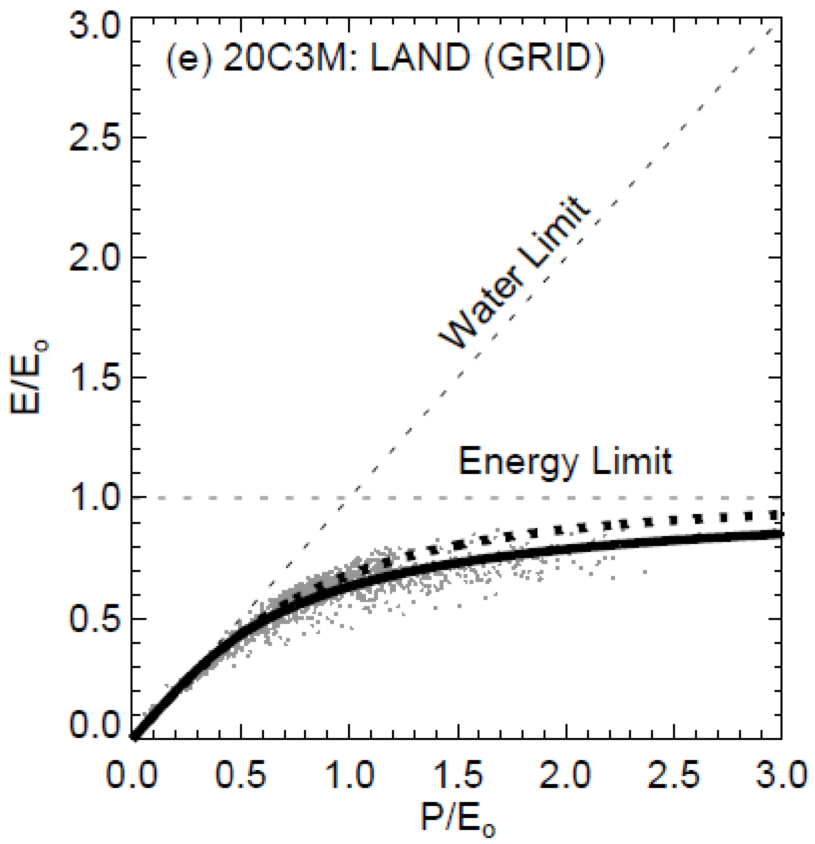
$$\mathrm{d}Q = \frac{Q}{P}\left(1 + \frac{E_0}{P}\right)\mathrm{d}P - \frac{Q}{P}\mathrm{d}E_0 = C_R\left(\left(1 + \frac{E_0}{P}\right)\mathrm{d}P - \mathrm{d}E_0\right)$$

or:

$$\frac{\mathrm{d}Q}{Q} = \left(1 + \frac{E_0}{P}\right)\frac{\mathrm{d}P}{P} - \frac{\mathrm{d}E_0}{P}$$

We see that the main control on runoff change is the runoff coefficient itself. The larger the runoff coefficient, the larger the runoff increases with increasing precipitation. Further, since the change in the potential evaporation is not so large, the runoff change is affected by the aridity index E_0*=P. The aridity index strengthens the sensitivity of runoff to rainfall.*

Very good point/s and a very clear commentary. We first note that this sensitivity framework is not actually in the cited references – as far as we are aware it is presented in this particular review for the first time! We agree that the resulting partial differentials are easier to interpret. We have also plotted the suggested form for the Budyko curve. In the modified Fig. 2e (below) we show the new form suggested by Prof Savenije:



Modified Fig. 2e New form of the Budyko curve is shown as a full heavy line and falls slightly below the original dashed line.

We conclude that the Savenije equation actually follows the data more closely than our original default equation. If we modified our default equation to use n=1.5 (as noted in the original figure caption) then it would be more or less the same as the Savenije equation.

Thus the new framework offered by Prof Savenije has some clear advantages. Given that we chose not to use the tunable parameter (n) it was suggested we could use this new and simpler form. Alternatively, in real catchments the additional parameter is actually needed to adequately account for the observed variation (Donohue et al 2011 J Hydrology) and a theoretical basis is currently being developed (Roderick & Farquhar 2011 WRR, Donohue et al 2012 J Hydrology) to express that parameter in terms of standard hydrologic quantities; mean storm depth, soil water holding capacity and effective rooting depth of the vegetation. That form also has a strong theoretical basis in terms of satisfying mathematical boundary conditions (Yang et al 2008 WRR) although we expect that the Savenije form is also likely well behaved at the boundaries.

We conclude that the presentation by Prof Savenije is novel and worthy of publication in its own right.

In response we have added a new Appendix to include this new derivation with appropriate modifications in the main text. The appendix includes a new figure (Fig. 7) that shows the excellent agreement with model output.

Further, we were aware that the maximum physical value is 1 in Fig. 3b. We simply could not draw the figure appropriately using our software. We have now tried harder and have made colour scales in Fig. 3 that scale from 0 to 1 and are more suitable from a physical point of view.

Response to Anonymous Comments by Referee 3

Referee comments in Italics

1. *Overall comments: This is a well written and clear article, which addresses an important research topic in climate science (why changes in precipitation under enhanced greenhouse gas concentrations are not changing at the Clausius-Clapeyron rate). It also highlights some potential pitfalls when applying rules derived (and valid) for latitude bands including both land and ocean areas (proportionality of changes in P-E to background P-E) to changes in land-only areas or to local changes over the oceans. Furthermore, it highlights an important misconception, i.e. that it is evapotranspiration that drives temperature changes under enhanced greenhouse gas forcing rather than the opposite, because most of the enhanced incoming longwave radiation is used for enhanced outgoing radiation at the surface. I have only minor comments on the article (see below) and thus recommend it being accepted subject to minor revisions.*

We thank the reviewer for the positive comments.

2. *Detailed comments: 1) P. 15264, lines 17-20: The construction of this sentence is a little convoluted and confusing. The three terms that are referred to should be more clearly highlighted and recognizable upon first reading. In addition, the sentence should note that most of the evapotranspiration changes occur over the oceans rather than land areas. Here is a suggested revision of this sentence: "In terms of global averages, we find [that] the climate climate model projections are dominated by changes in only three terms of the surface energy balance: 1) an increase in the incoming long-wave irradiance, and the respective responses in 2) outgoing longwave irradiance and 3) evaporative flux (the latter being much smaller than the other two terms and mostly restricted to the oceans).*

That is better. We will incorporate that into the revision. Thank you.

3. *2) P. 15274, line 11: The following paragraph is mostly based on the numbers in Table 2, but I found Fig. 5 more straightforward to interpret upon first reading. I would suggest to add in the parenthesis "(Table 2)" also a reference to Fig. 5, e.g: "(Table 2; see also Fig. 5 for a summary of the changes between the two periods)".*

Again – that is better. We will incorporate that into the revision. Thank you.

4. *3) P. 15275, line 6: Add "over the oceans" after "in the latent heat flux" (same comment as 1): most of the changes in evaporation occur over the oceans)*

Agreed and done.

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. When we came to correct the spelling we could not locate a spelling mistake in the manuscript?

(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 in the CMIP3 archive do not actually project this at the local scales that matter for impacts and for management. Those local scales are of primary interest for hydrologists.

After reading this comment and comment (6) below, we think that the problems highlighted by the reviewer arise because of the abstract.

In response we have completely rewritten the abstract to highlight key results for hydrologists and for atmospheric/climate scientists along the lines we indicated in the original response to the review.

(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. That remains an important research question.

(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 (section 5) 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.

See response to comment 2 above.

Additional Comment by Prof Sivapalan (received by email after the review)

It was suggested we examine a recent paper and contrast their results with our results as follows:

Kumar, S., Lawrence, D. M., Dirmeyer, P. A., and Sheffield, J.: Less reliable water availability in the 21st century climate projections, Earth's Future, n/a-n/a, 10.1002/2013ef000159, 2014.

This turned out to be a highly relevant paper and we have added a comparative analysis of those results in two new paragraphs in the discussion.

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

Michael L. Roderick[1,2,3], Fubao Sun[2,3], Wee Ho Lim[2,3,4], Graham D. Farquhar[2,3]

[1] Research School of Earth Sciences and [2] Research School of Biology, The Australian National University, Canberra, ACT 0200, Australia

[3] Australian Research Council Centre of Excellence for Climate System Science

[4] Currently at Department of Civil Engineering, Tokyo Institute of Technology, Tokyo 152-8552, Japan

Correspondence to: Michael L. Roderick (michael.roderick@anu.edu.au)

Manuscript Details:

File:	GlobalWater_Hess_v6.doc
Date:	24 March 2014
Details:	6500~~6200~~ Words, 7~~6~~ Figures, 2 Tables

Abstract

Climate models project increases in globally averaged atmospheric specific humidity that are close to ~~at~~ the Clausius-Clapeyron (CC) value of around 7% K^{-1} whilst projections for mean annual global precipitation (P) and evaporation (E) are somewhat muted at around 2% K^{-1}. Such global projections are useful summaries but do not provide guidance at local (grid box) scales where impacts occur. To bridge that gap in spatial scale, previous research has shown that the ~~following~~ "wet get wetter and dry get drier" relation, $\Delta(P\text{-}E) \propto P\text{-}E$, follows CC scaling when the projected changes are averaged over latitudinal zones. ~~holds for zonal averages in climate model projections.~~ Much of the impacts research has been based on an implicit assumption that this CC relation also holds at local (grid box) scales but that has not previously been examined. In this paper we ~~first~~ find that the simple latitudinal average CC scaling relation does not hold at local (grid box) scales over either ocean or land. ~~test whether that relation holds at grid box scales over ocean and over land. We find that the zonally averaged relation does not hold at grid box scales.~~ This means that in terms of *P-E*, the climate models do not project that the "wet get wetter and dry get drier" at the local scales that are relevant for agricultural, ecological and hydrologic impacts. ~~We further find that the zonally averaged relation does not hold over land – it is specific to zonal averages over the ocean.~~ In an attempt to develop a simple framework for local scale analysis ~~As an alternative we~~ we found that the climate model output shows a remarkably close relation to the long standing Budyko framework of catchment hydrology. ~~tested whether the long standing Budyko framework of catchment hydrology~~ We subsequently use the Budyko curve and find that the local scale changes in *P-E* projected by climate models are dominated by changes in *P* while the changes in net irradiance at the surface due to greenhouse forcing are small and only play a minor role in changing the mean annual *P-E* in the climate model projections. ~~could be used to synthesise climate model projections over land. We find that climate model projections of $\Delta(P\text{-}E)$ out to the year 2100 conform closely to the Budyko framework. The analysis also revealed that climate models project little change in the net irradiance at the surface.~~ To further understand the apparently small changes in net irradiance ~~that result~~ we also examined projections of ~~the~~ key surface energy balance terms. In terms of global averages, we find that the climate model projections are dominated by changes in only three terms of the surface energy balance: 1) an increase in the incoming long-wave irradiance, and the respective responses 2) in outgoing longwave irradiance and 3) in the evaporative flux with the latter change being much smaller than the former two terms and mostly restricted to the oceans. ~~In~~

Formatted: Font: Italic

Formatted: Font: Italic

Formatted: Font: Italic

Formatted: Font: Italic

Formatted: Font: Italic

Formatted: Font: (Default) Times New Roman, Not Italic, English (U.K.)

Formatted: Font: (Default) Times New Roman, Not Italic, English (U.K.)

Formatted: Font: (Default) Times New Roman, Not Italic, English (U.K.)

Formatted: Font: (Default) Times New Roman, Not Italic, English (U.K.)

Formatted: Font: (Default) Times New Roman, Not Italic, English (U.K.)

Formatted: Font: (Default) Times New Roman, Not Italic, English (U.K.)

~~terms of global averages, we find the climate model projections are dominated by changes in only three terms of the surface energy balance; an increase in the incoming longwave irradiance while the responses are (mostly) restricted to the outgoing longwave irradiance with a small change in the evaporative flux. Because the change in outgoing longwave irradiance is a function of the change in surface temperature, we show that the precipitation sensitivity (i.e., 2% K~~ ~~$^{-1}$~~ ~~) is an accurate summary of the partitioning of the greenhouse-induced surface forcing.~~ The small fraction of the realised surface forcing that is partitioned into *E* explains why the hydrologic sensitivity (2% K^{-1}) is so much smaller than CC scaling (7% K^{-1}). ~~With that we demonstrate that the precipitation sensitivity (2% K~~ ~~$^{-1}$~~ ~~) is less than the CC value (7% K~~ ~~$^{-1}$~~ ~~) because most of the greenhouse-induced surface forcing is partitioned into outgoing longwave irradiance (instead of evaporation).~~ Much public and scientific perception about changes in the water cycle has been based on the notion that temperature enhances *E*. That notion is partly true but has proved an unfortunate starting point because it has led to misleading conclusions about the impacts of climate change on the water cycle. A better general understanding of the potential impacts of climate change on water availability that are projected by climate models will surely be gained by starting with the notion that the greater the enhancement of *E*, the less the surface temperature increase (and vice versa). That latter notion is based on the conservation of energy and is an underlying basis of climate model projections.~~In essence, the models respond to elevated [~~ ~~CO_2~~ ~~] by an increase in atmospheric water vapour content that increases the incoming long-wave irradiance at the surface. The surface response is dominated by a near equal increase in outgoing long-wave irradiance with only minor changes in other terms of the surface energy balance.~~

Formatted: Font: Italic

Formatted: Superscript

Formatted: Superscript

Formatted: Font: Italic

Formatted: Justified, Space Before: 6 pt, Line spacing: 1.5 lines

1 Introduction

The water cycle is like a vast heat engine with water evaporating at the surface and the vapour subsequently condensing at relatively colder temperatures high up in the atmosphere before precipitating and thereby closing the atmospheric component of the water cycle. The cycle begins with evaporation that by itself consumes around 80% or so of the available energy at the surface (~~Monteith, 1981;~~ Trenberth et al., 2009; Wild et al., 2013). Because of the energetic importance, understanding global scale changes in climate requires an understanding of global scale changes in the water cycle. However, the water cycle is not just of interest at global scale. Many of the key impacts of anthropogenic climate change, e.g., on agriculture, water resources, terrestrial ecology, etc., are projected to occur via changes in water availability. Of particular interest are changes in precipitation (*P*), evaporation (*E*) and their difference (*P*-*E*). In that respect two key results have emerged from previous syntheses of climate model output. First, the atmospheric specific humidity is projected to increase at the Clausius-Clapeyron (CC) value of around 7% K^{-1} (Held and Soden, 2000). That result is not programmed into the models - rather it emerges and is more or less the same as the original constant relative humidity assumption made by Arrhenius in the first detailed calculations of the impact of changing atmospehric CO_2 (Arrhenius, 1896; Ramanathan and Vogelmann, 1997). A second emergent projection from climate models is for global *P* to increase by around 1 to 3% K^{-1} that is often summarised by the 2% K^{-1} statement (Boer, 1993; Allen and Ingram, 2002). These global scale syntheses are useful because they enable scientists to better understand and interpret the climate model output. More importantly, they offer ongoing opportunities to confront the model projections with observations (e.g., Wu et al., 2013; Wentz et al., 2007; Liepert and Previdi, 2009; Sherwood et al., 2010; Paltridge et al., 2009; Vonder Haar et al., 2012).

Field Code Changed

Field Code Changed

Field Code Changed

Simplifying projected changes in the global water cycle using temperature-based scaling relations is also useful because it readily relates to widely discussed projections and political targets, e.g., a 3 K increase in globally averaged surface temperature for a doubling of CO_2 (IPCC, 2007). However, the global results themselves have little direct application for impact studies because the impacts are local and not global. Some typical questions of direct relevance to impacts include; will it rain more or less where I live?, or, will the runoff increase or decrease in the local catchment over the coming century?, and so on. Local scale questions like those cannot be answered using global averages. Simulations and projections of key water cycle variables (*P*, *E*, *P-E*) are readily available at local (grid box) scales for all climate models. For example, the widely used CMIP3 (Coupled Model Intercomparison Project Phase 3) simulations and projections are summarised in the Global Water Atlas (Lim and Roderick, 2009). Similar summaries are expected to become available shortly for the newly developed CMIP5 archive. Those summaries faithfully represent the simulations and projections, but for scientific understanding, some level of synthesis is desirable.

Held and Soden (2006) extended the globally averaged results by studying changes projected to the end of the 21st century in the latitudinal (i.e., zonal) averages of key water and energy variables. Using a multi-model ensemble mean derived from CMIP3 models they uncovered a simple relation where the projected change in *P-E* in each latitudinal zone scaled with *P-E*, i.e., $\Delta(P\text{-}E) \propto P\text{-}E$, where the scaling coefficient was the CC value (7% K^{-1}) multiplied by the temperature difference. In attempting to summarise their result they used the phrase the "wet get wetter and dry get drier". By that they meant that if *P-E* was greater than zero, then one could consider the surface to have a surplus of water (i.e., the hydrologic equivalent of runoff) and in that sense it was wet. Further, the change, $\Delta(P\text{-}E)$, would have the same sign (±) as *P-E*, hence the wet get wetter (and vice versa). That definition has some problems when trying to interpret land and ocean changes in a single integrative framework (see below). Despite that difficulty, the emergent relation remains an important insight for climate science -because one can readily understand projected changes in the *zonally averaged* poleward transport of heat and moisture from the *zonally averaged* projected changes in *P-E* (Held and Soden, 2006).

Given the now widespread use of the "wet get wetter and dry get drier" phrase it is important to briefly revisit, and understand, what the results presented by Held and Soden (2006) actually showed. Their zonal averages included both ocean and land. At most latitudes, *P* and *E* are dominated by exchanges over the ocean (Oki and Kanae, 2006; Lim and Roderick, 2009) and zonal averages will be mostly determined by exchanges over the ocean. Held and Soden (2006, p. 5693) were well aware of this limitation and also noted the key difference between land and ocean; over land the long term average *E* must be less than or equal to *P*. In contrast, water is always available for evaporation over the ocean and *E* is not constrained by

P. This creates a problem for interpreting the results. In particular, if we adopt their definition of wet, i.e., *P*-*E* ≥ 0, then all land is classified as wet as is around half the ocean while the remaining part of the ocean will be defined as dry. That is clearly an unsatisfactory basis for interpretation. More generally, the different behaviour of land and ocean with respect to the water cycle makes it difficult to treat land and ocean in one common interpret~~at~~ive framework (Roderick et al., 2012). Given that the zonal averages are dominated by the oceanic components, it follows that the Δ(*P*-*E*) ∝ *P*-*E* relation should ~~will~~ be mostly relevant to the ocean. With that in mind, we reinterpret the Held and Soden (2006) result by first noting that the ocean surface is always wet irrespective of the values of *P* and *E*. Instead, *P*-*E* is a useful index of the salinity status of the surface ocean water (Durack et al., 2012). On that basis, a better description of their finding is that the *fresh get fresher and salty get saltier*. Two important questions arise. First, does the *fresh get fresher and salty get saltier* framework hold at individual grid boxes over the ocean? Second, is it possible to synthesise the model projections over land either in terms of either zonal averages, or more importantly, for the individual grid boxes, because the latter is the relevant scale for assessing climate impacts.

The aim of this paper is to address the two above-noted questions. To maintain consistency in the interpretation we use the same climate model output (CMIP3) as originally used by Held and Soden (2006) and follow their analysis by focussing on changes in the mean annual water and surface energy balances over climatic time scales (here we use 30 year averages). The paper begins with a brief overview of projected changes in the water cycle for the globe, and for land and ocean separately, and then tests whether the previous zonally averaged results for changes in *P*-*E* also hold at local (grid box) scales. We then extend earlier work by incorporating projected changes in the surface energy balance and show that the climate model projections over land conform closely to the long established Budyko framework of catchment hydrology (Budyko, 1948, 1974, 1982). We finalise the paper by presenting a ~~new and~~ novel framework that moves beyond the simple temperature-based scaling of the hydrologic impact of climate change to a more general surface energy balance framework. That new perspective is used to understand how projected changes in the water cycle are simultaneously related to projected changes in greenhouse-induced surface forcing and surface temperature in climate models.

2 Climate Model Simulations and Projections

Following Held and Soden (2006), we use the same output from IPCC AR4 models available in the CMIP3 archive for the 20th century simulations (20C3M scenario) and 21st century projections (A1B scenario) (Meehl et al., 2007). A multi-model ensemble mean (2.5° × 2.5° spatial resolution) was constructed using 39 runs from 20 different climate models for precipitation (*P*) and evaporation (*E*). Full details of all individual model runs (including maps and summary tables) are available in the Global Water Atlas (Lim and Roderick, 2009). The mean annual water balance is represented by averages calculated for both the 1970-1999 and 2070-2099 periods. We also calculated averages over the same time periods for all surface energy balance terms (units: W m^{-2}); incoming ($R_{S,i}$) and outgoing ($R_{S,o}$) shortwave and longwave ($R_{L,i}$, $R_{L,o}$) irradiance as well as the latent (*LE*, with *L* (J kg^{-1}) the latent heat of vaporisation and *E* (kg m^{-2} s^{-1}) the evaporation rate~~)~~) and sensible (*H*) heat fluxes. The rate of change in enthalpy (~~Storage of heat (~~*G*) is calculated as the residual of the above terms.

Field Code Changed
Field Code Changed
Field Code Changed
Formatted: Superscript
Formatted: Superscript
Formatted: Font: Italic

The hydrologic analysis (sections 3, 4) uses the traditional depth units for *P* and *E* (mm per annum, mm a^{-1}) whilst the surface energy balance analysis (section 5) is based on energetic units (all heat fluxes have units W m^{-2}). In that sense *E* in the hydrologic analysis (units: mm a^{-1}) is related to *LE* in the energetic analysis (units: W m^{-2}) via the latent heat of vaporisation and the density of liquid water.

Formatted: Font: Italic
Formatted: Font: Italic
Formatted: Superscript
Formatted: Font: Italic
Formatted: Superscript
Formatted: Font: Italic

3 Projected Changes in the Water Cycle over Land and Ocean

3.1 Changes in P and E over Land and Ocean

Projected changes for the globe and for the ocean and land components are summarised in Table 1. Global *P* and *E* are both projected to increase by around 4.5% by the end of the 21st century. The global mean surface temperature change (per the A1B scenario used here) is 2.8 K and the projected change in global *P* and *E* is equivalent to 1.6% K^{-1} and consistent with results noted elsewhere (Boer, 1993; Allen and Ingram, 2002). As expected the projection shows that *P* increases faster than *E* over land leading to more runoff (Nohara et al., 2006) with the ocean behaving in the opposite fashion as must happen to ensure global mass balance. In preparing Table 1 we have ignored changes in the atmospheric water content (i.e., humidity) because that makes little difference to the overall mass balance. In particular, the globally averaged water content of the atmosphere is around 30 kg m^{-2} when expressed per unit of global surface (Oki and Kanae, 2006; Wentz et al., 2007; Vonder Haar et al., 2012). The equivalent depth of liquid water is 30 mm and is projected to change by some 7% K^{-1}. Hence for a warming of 2.8 K, the projected change in the mass of water in the atmosphere is ($30 \times 0.07 \times 2.8 =$) 5.9 mm (equivalent depth of liquid water). Taken over the 100-year period under consideration here, the change is too small (= 5.9 mm/100 a = 0.059 mm a^{-1}) to have a measureable impact on either the global mean annual P or E. This raises an interesting point – the absolute change in water content of the atmosphere plays little role in the global mass balance but that same change leads to a substantial fraction of the global warming projected by the climate models via the so-called positive water vapour feedback (Held and Soden, 2000; Russell et al., 2013). We will return to this important point in the Discussion and Conclusions (Section 6).

Table 1 here

Figure 1 here

Our results confirm the original $\Delta(P\text{-}E) \propto P\text{-}E$ relation for zonal averages (Held and Soden, 2006) (Fig. 1b). We find that this relation does not hold over the land component (Fig. 1e). At individual grid boxes there is no relation between $\Delta(P\text{-}E)$ and $(P\text{-}E)$ over either ocean or land (Fig. 1c, 1f). We conclude that the original scaling relation, $\Delta(P\text{-}E) \propto (P\text{-}E)$ (Fig. 1b) is of most relevance over the ocean and only applies to zonal averages. It is not applicable at local (grid box) scales over either the ocean or land.

3.2 Relating *P* and *E* over Land using the Budyko Curve

In terms of the mean annual water balance, water is always available for evaporation over the ocean and E there can be larger than P, whilst over land, $E \leq P$. At individual grid boxes the multi-model ensemble mean respects those physical facts (Figs 2a, 2d). Over land, the most general approach relating to E to P is the Budyko (supply-demand) framework (Budyko, 1948, 1974; Turc, 1954; Mezentsev, 1955; Pike, 1964; Fu, 1981; Milly, 1994; Dooge et al.,

Formatted: English (U.K.)
Formatted: Font: Italic, English (U.K.)
Formatted: English (U.K.)
Formatted: Font: Italic, English (U.K.)
Formatted: English (U.K.)
Formatted: English (U.K.)
Formatted: English (U.K.)
Field Code Changed
Formatted: English (U.K.)
Field Code Changed
Formatted: English (U.K.)
Field Code Changed
Formatted: English (U.K.)
Formatted: English (U.K.)
Formatted: English (U.K.)
Formatted: English (U.K.)
Field Code Changed
Formatted: English (U.K.)
Formatted: English (U.K.)
Field Code Changed
Formatted: English (U.K.)
Formatted: English (U.K.)
Field Code Changed
Formatted: English (U.K.)
Formatted: English (U.K.)
Formatted: English (U.K.)
Formatted: English (U.K.)
Field Code Changed
Field Code Changed
Field Code Changed
Formatted: English (U.K.)

1999; Koster and Suarez, 1999; Choudhury, 1999; Zhang et al., 2001; Arora, 2002; ~~Koster et al., 2006;~~ Yang et al., 2007; Yang et al., 2008; Gerrits et al., 2009; Roderick and Farquhar, 2011; Donohue et al., 2011; Renner and Bernhofer, 2012). On that approach the (steady state) partitioning of P between E and runoff (= P-E here) is treated as a functional balance between the supply of water from the atmosphere (P) and a constraint on the upper limit for E, here denoted E_o, and defined as the liquid water equivalent of the net irradiance (= R_N/L). R_N is calculated from the mul~~i~~ti-model ensemble mean ~~output~~ ($R_N = R_{S,i} - R_{S,o} + R_{L,i} - R_{L,o}$). We use the Mezenstev-Choudhury-Yang equation (Mezentsev, 1955; Choudhury, 1999; Yang et al., 2008) to calculate E,

$$E = \frac{P\,E_o}{\left(P^n + E_o^n\right)^{1/n}} , \qquad (1)$$

where n is the catchment properties parameter that modifies the partitioning of P between E and runoff (see Roderick and Farquhar (2011) for full details). In catchments studied to date the values of n range from 0.6 to 3.6 but most fall within a smaller range of 1.5 to 2.6 (Choudhury, 1999; Yang et al., 2007; Yang et al., 2008; Donohue et al., 2011). Setting n=1.9 reproduces the original Budyko curve (Donohue et al., 2011). Note that a higher value of n implies a higher value of E for given P and E_o.

Eq. (1) has a strong foundation being ~~This semi-empirical equation is~~ based on mass and energy conservation and the fact that when E is water-limited (e.g., arid desert), $E \to P$, and when E is energy-limited (e.g., tropical rainforest), $E \to E_o$. Note that over the ocean, large quantities of heat can be advected (by ocean currents) and E_o does not set a useful upper limit at local (grid box) scales (Fig. 2b). E_o does set a limit at the global scale (Allen and Ingram, 2002; O'Gorman and Schneider, 2009), and in the model output, E_o sets a limit to E over the ocean in the zonal averages (Fig. 2c).

Figure 2 here

We use Eq. ~~n~~ (1) to calculate E at individual grid boxes over land and express the result using a traditional Budyko diagram. The result at the grid box scale is stunning (Fig. 2e). It is important to note here that this is an independent test since the climate models do not use the Budyko curve ~~approach~~ to calculate the partitioning of water and heat at the surface. They cannot – the Budyko framework only applies to long-term averages (Donohue et al., 2007). Rather, each climate model solves the surface energy and water balance and steps (usually every 15 mins) through time. When aggregated to 30 year averages our results show that the multi-model ensemble mean ~~output~~ conforms to the Budyo framework. We also aggregated the land data into 10° latitudinal zones and this also conforms to the ~~a~~ Budyko curve (Fig. 2f). This is not a surprise given the results in Fig. 2e. In particular, the Budyko framework is based on the fundamentals of mass and energy conservation and the asymptotic limits inherent to the approach ~~result will~~ transfer accross spatial scales. In that sense the result shown in Fig. 2f simply follows from Fig. 2e. We also tested the Budyko framework using climate model output for the end of the 21st century (2070-2099, A1B) and found almost identical results (not shown).

4 Understanding Projected Changes in the Water Cycle over Land

The fact that the climate model output conforms to the Budyko framework at grid box scales (Fig. 2e) is useful. Firstly, it establishes that over climatic time scales, the partitioning of P between E and runoff (= P-E) in climate models is consistent with nearly a century of accumulated hydrologic experience embodied in the Budyko curve. Secondly, it opens up the possibility of using the Budyko framework to unravel the model projections of hydrologic change at the surface into the underlying causes. For that we use the differential form of the Budyko curve (Roderick and Farquhar, 2011),

$$dE = \frac{\partial E}{\partial P} dP + \frac{\partial E}{\partial E_o} dE_o + \frac{\partial E}{\partial n} dn \quad , \qquad (2)$$

with the partial differentials given by,

$$\frac{\partial E}{\partial P} = \frac{E}{P}\left(\frac{E_o^n}{P^n + E_o^n}\right) \quad , \qquad (3a)$$

$$\frac{\partial E}{\partial E_o} = \frac{E}{E_o}\left(\frac{P^n}{P^n + E_o^n}\right) \quad , \qquad (3b)$$

$$\frac{\partial E}{\partial n} = \frac{E}{n}\left(\frac{\ln(P^n + E_o^n)}{n} - \frac{(P^n \ln P + E_o^n \ln E_o)}{P^n + E_o^n}\right) \qquad . \tag{3c}$$

Note that the partial differentials are all functions of the existing climate (P, E_o) and the catchment properties parameter (n). We further note that century-scale changes in the catchment properties parameter (dn) are likely related to changes in vegetation (Roderick and Farquhar, 2011; Donohue et al., 2012). Given that the climate models (in the CMIP3 archive) do not simulate changes in land cover we assume no change in the parameter value (dn = 0). With that assumption, the change in P-E is given by,

$$d(P-E) = \varepsilon_P \; dP - \varepsilon_o \; dE_o \qquad , \tag{4a}$$

with the sensitivity coefficients defined by,

$$\varepsilon_P = 1 - \frac{\partial E}{\partial P} \quad , \quad \varepsilon_o = \frac{\partial E}{\partial E_o} \qquad . \tag{4b}$$

(Note: Please see appendix A for a physical interpretation of this sensitivity framework using an alternate mathematical form of the Budyko curve.) The Budyko framework is not intended for use in the cryosphere since additional long-term mass balance terms (snow/ice) violate the mass balance assumptions.~~and w~~ We limit the calculations to the latitudinal range 60°S to 60°N.

Figure 3 here

The results show that the theoretically based estimate (Fig. 3e) more or less replicates the model output (Fig. 3f). In more detail, $\Delta(P\text{-}E)$ is generally much more sensitive to variations in ΔP (Fig. 3a) than to variations in ΔE_o (Fig. 3b) as expected (Roderick and Farquhar, 2011; Donohue et al., 2011).~~-~~Differences in ΔP between individual grid boxes can be large (range -267 mm a^{-1} to +579 mm a^{-1}) with the change, averaged over all grid boxes of +53 mm a^{-1} (± {1sd} 89 mm a^{-1}). The spatial variations in ΔE_o are smaller (range -30 mm a^{-1} to +185 mm a^{-1}) with the change, averaged over all grid boxes of +47 mm a^{-1} (± {1sd} 30 mm a^{-1}). Because the sensitivity of $\Delta(P\text{-}E)$ to change in ΔE_o is relatively smaller (Fig. 3b), and the variations in

ΔE_o are also relatively small (Fig. 3d), the final predicted map of $\Delta(P\text{-}E)$ is dominated by the sensitivity to, and variations in, ΔP.

Figure 4 here

The theoretical predictions of $\Delta(P\text{-}E)$ (Fig. 3e) are compared with the changes projected over the land surface by the climate models (Fig. 3f) in Fig. 4. The theoretical model accounts for around 82% of the variation in the GCM projections of $\Delta(P\text{-}E)$ over the global land surface (Fig. 4c). Note that $\Delta(P\text{-}E)$ is more or less independent of the variations due to changes in E_o (Fig. 4b) and is instead dominated by the variations due to changes in P (Fig. 4a) confirming our earlier deductions. (See Appendix A for a physically based interpretation of that result.) In simple terms, whether $P\text{-}E$ increases or decreases in a given place depends mostly on changes in P.

5 Understanding Projected Changes in the Surface Water and Energy Balance

The results of the theoretical analysis (Section 4) showed that most of the grid box scale projected changes in $P\text{-}E$ were due to changes in P with limited impact due to variations in E_o. There was very little spatial structure in the maps of ΔE_o (Fig. 3d) consistent with the notion of an increase in well mixed greenhouse gases but we noted only a small change in E_o (+47 ± 30 mm a^{-1}, mean ± 1sd) despite the fact that the projected increase in global mean surface temperature is nearly 3 K. Understanding why the projected changes in E_o are so small is the key to understanding why P and E are apparently so insensitive to changes in greenhouse forcing in the climate models. That is the focus of this section.

5.1 Projected Changes in the Surface Energy Balance

The surface energy balance is defined as,

$$R_{S,i} - R_{S,o} + R_{L,i} - R_{L,o} - LE - H - G = 0 \quad , \tag{5}$$

with incoming and outgoing shortwave ($R_{S,i}$, $R_{S,o}$) and longwave ($R_{L,i}$, $R_{L,o}$) irradiance being balanced by the latent (LE) and sensible (H) heat fluxes while the rate of change in enthalpy ~~storage~~ (positive into the surface) is denoted G. To help understand why the projected change in net irradiance, R_N (= $R_{S,i}$ - $R_{S,o}$ + $R_{L,i}$ - $R_{L,o}$) is small, we compiled estimates of the surface energy balance variables from the multi-model ~~climate model~~ ensemble mean for the two periods in question (Table 2).

Table 2 here

In terms of the climatology (1970-1999) the magnitude of terms in the simulated surface energy balance are generally consistent with current understanding (Trenberth et al., 2009; Wild et al., 2013) (Table 2, also see Fig. 5 for a summary of changes between the two time periods). At the outset we focus on understanding changes in the global energy balance and consider any differences between land and ocean later. For a perfect blackbody at 286.8 K (= 13.6 °C, 1970-1999, Table 2) we expect the outgoing longwave flux would increase by around ($dR_{L,o}/dT = 4\,\sigma\,T^3\,dT \sim 5.4$ W m^{-2} K^{-1}) 5.4 W m^{-2} for every 1 K surface temperature increase. Hence for the projected 2.8 K surface T increase (Table 2) we expect $\Delta R_{L,o}$ to be around +15.1 W m^{-2}. The model projection is very close to that value (+14.8 W m^{-2}) implying that the global surface is very close to a blackbody (as expected). There is a projected reduction in shortwave irradiance arriving at the surface ($\Delta R_{S,i}$ = -1.7 W m^{-2}) that is exactly offset by a reduction in shortwave irradiance leaving the surface ($\Delta R_{S,o}$ = -1.7 W m^{-2}) because of a decrease in surface albedo. Consequently, there is no net change in the absorbed shortwave irradiance and any change in the global net irradiance (R_N) can only be due to change in the longwave components. The projection is for a small reduction in the sensible heat flux (ΔH = -1.1 W m^{-2}) with an equivalent rate of increase in enthalpy ~~flux of heat taken up by an increase in storage~~ (ΔG = +1.1 W m^{-2}) that is almost entirely located in the ocean (Table 2) as expected (Pielke Sr, 2003; Levitus et al., 2005). With those relatively minor changes out of the way, the major changes in the surface energy balance are in the incoming and outgoing longwave irradiance with a smaller residual change in the latent heat flux that is mostly restricted to the global ocean (Fig. 5). What is critical in terms of changes to the water cycle is the ultimate fate of the increase in incoming longwave irradiance. In the multi-model ensemble mean, most of that increase is simply returned to the atmosphere by an increase in outgoing longwave irradiance ($\Delta R_{L,o}$ = +14.8 W m^{-2}) with only a small residual fraction being partitioned into a non-radiative component - the latent heat flux ($L\Delta E$ = +3.7 W m^{-2}). In summary, the reason that models project ~~a~~ relatively small changes in global E (and hence P) is that the models partition a small fraction of the increase in incoming longwave irradiance into the latent heat flux. Instead, ~~in the model ensemble,~~ the increased incoming longwave irradiance mostly increases the outgoing long-wave irradiance. In essence, in the climate model projections, most of the realised surface (radiative) forcing is in the longwave part of the spectrum and is not transformed into another type of energy ~~like~~ such as a convective flux.

Figure 5 here

The same basic pattern, i.e., a large increase in incoming longwave irradiance ($\Delta R_{L,i}$) that is mostly partitioned into outgoing longwave irradiance ($\Delta R_{L,o}$) with a smaller residual increase in $L\Delta E$ also holds separately over land and ocean although there are some relatively minor differences between land and ocean (Fig. 5). Over the ocean there are slight reductions in both incoming and outgoing solar radiation with a small overall reduction in absorbed solar radiation (= $\Delta R_{S,i}$ - $\Delta R_{S,o}$ = -1.8 – (-1.4) = -0.4 W m^{-2}), a larger reduction in the sensible heat flux (ΔH = -2.0 W m^{-2}) while virtually all of the global increase in enthalpy ~~storage~~ occurs in the ocean (ΔG = +1.5 W m^{-2}). In contrast, over land there are slight increases in absorbed solar radiation (= $\Delta R_{S,i}$ - $\Delta R_{S,o}$ = -1.5 – (-2.3) = +0.8 W m^{-2}) while the fraction of the increase in incoming longwave irradiance ($\Delta R_{L,i}$ = + 21.7 W m^{-2}) partitioned into the outgoing longwave irradiance ($\Delta R_{L,o}$ = + 19.6 W m^{-2}) is larger with only a very small residual energy flux available to enhance the latent ($L\Delta E$ = + 1.6 W m^{-2}) and sensible (ΔH = +1.3 W m^{-2}) heat fluxes. Those minor differences aside, the key finding is that the globally averaged increase in incoming longwave irradiance at the surface ($\Delta R_{L,i}$) is mostly partitioned into the outgoing longwave irradiance ($\Delta R_{L,o}$) with a small and essentially residual increase in the latent heat flux ($L\Delta E$).

5.2 Synthesis

For the purposes of understanding model projections of changes in the global water cycle it is clear from the previous analysis that we can ignore changes in the shortwave radiative components, the sensible heat flux and the rate of change in enthalpy ~~storage term~~. With that, we approximate the global projected change by,

$$\Delta R_{L,i} \approx \Delta R_{L,o} + L\Delta E \qquad . \qquad (6)$$

For the climate change projection being considered here, we previously noted that global P (and E) increases by 1.6% K^{-1} and the average T increase is 2.8 K (Table 1). What has not been readily apparent before is that this simple two statement summary (ΔP = 1.6% K^{-1}, ΔT = 2.8 K) already *contains all of the information* needed to reconstruct the projected changes in the global surface energy balance.

To see that we first define the incremental flux ratio,

$$x = \frac{L\Delta E}{\Delta R_{L,o}} \qquad . \qquad (7)$$

Combining that with Eq. ~~n~~ (6), the evaporative fraction of the increase in incoming longwave irradiance is given by,

$$\frac{L\Delta E}{\Delta R_{L,i}} = \frac{x}{1+x} \qquad , \qquad (8a)$$

and the remaining thermal fraction is,

$$\frac{\Delta R_{L,o}}{\Delta R_{L,i}} = \frac{1}{1+x} \qquad . \qquad (8b)$$

The key point is that one can readily convert a statement on the % change in P per degree of warming into an estimate of x. In addition the projected surface warming gives the increase in outgoing longwave irradiance. Combining those two pieces of information allows one to reconstruct the projected change. To do that we first note that the change in global P is equal to the change in global E and that a surface warming of 1 K is equivalent to an increase in the outgoing blackbody irradiance ($dR_{L,o}/dT = 4\ \sigma\ T^3$ ~~dT~~ ~ 5.4 W m^{-2} K^{-1} ~~dT~~) of 5.4 W m^{-2}.

Setting global E as 82.3 W m^{-2} (Table 2), the 1.6% K^{-1} increase in global E can be converted to an estimate of x as follows,

$$x = \frac{1.6}{100}(82.3)\frac{1}{5.4} = (1.6)(0.15) = 0.24 \qquad . \tag{9}$$

With x = 0.24, the incremental evaporative and thermal fractions (Eq. ~~n~~8) are respectively,

$$\frac{L\Delta E}{\Delta R_{L,i}} = \frac{0.24}{1+0.24} = 0.19 \quad , \qquad \frac{\Delta R_{L,o}}{\Delta R_{L,i}} = \frac{1}{1+0.24} = 0.81 \qquad . \tag{10}$$

For ΔT = 2.8 K, the increase in outgoing blackbody longwave from the surface $\Delta R_{L,o}$ is (5.4 × 2.8 =) +15.1 W m^{-2}. With x = 0.24 (Eq. ~~n~~9), $L\Delta E$ will be (0.24 × 15.1 =) +3.6 W m^{-2} and the increase in incoming longwave irradiance $\Delta R_{L,i}$ is (15.1 + 3.6 =) +18.7 W m^{-2}. This independent reconstruction is very similar to the values calculated directly from the multi-model ensemble mean (Table 2, $\Delta R_{L,i}$ = +18.6 W m^{-2}, $\Delta R_{L,o}$= +14.8 W m^{-2}, $L\Delta E$ = +3.7 W m^{-2}).

One important consequence of the energy balance framework used here is that it makes it clear that any increase in evaporation will reduce the surface temperature increase (and vice versa). We can express that physical relation by rewriting Eq. ~~n~~(6) as,

$$\Delta R_{L,i} \approx \Delta R_{L,o} + L\Delta E = 4\sigma T^3 \Delta T + L\Delta E \quad \Rightarrow \quad \Delta T \approx \frac{\Delta R_{L,i} - L\Delta E}{4\sigma T^3} \qquad . \tag{11}$$

The inter-relationships between changes in the incoming ($\Delta R_{L,i}$) and outgoing ($\Delta R_{L,o}$, $L\Delta E$) fluxes, the change in surface temperature and the percentage enhancement in the global P are summarised in Fig. 6. Note that if global P (and hence E) did turn out to increase at the CC value of 7% K^{-1} (e.g., Wentz et al., 2007) instead of the 1.6% K^{-1} as per the projection considered here, then the increase in surface temperature would be smaller at around +1.7 K (Fig. 6).

Figure 6 here

6 Discussion & Conclusions

Our study confirms that in the climate models, the relation $\Delta(P\text{-}E) \propto P\text{-}E$ holds in terms of zonal averages over the ocean, with the scaling coefficient being the CC value (7% K^{-1}) multiplied by the temperature difference (Fig. 1b) (Held and Soden, 2006)~~ holds in terms of zonal averages over the ocean~~. Further investigations showed that this relation does not hold at the grid box scale over the ocean (Fig. 1c) or the land (Fig. 1f~~e~~). That is important. For example, imagine one were to identify a scaling relation like $\Delta(P\text{-}E) \propto P\text{-}E$ in local scale (e.g., grid box) ~~*oceanic*~~ *observations*. Such a result would actually constitute a falsification of the climate model projections. In that respect what the climate models ~~ensemble~~ project~~s~~ is an emergent scale dependent (zonal) relation that is useful to help understand projected changes in the zonally averaged poleward transport of heat and moisture (Held and Soden, 2006). But that same relation does not hold at local grid box scales and is therefore not a useful summary of impacts at the local scale. ~~We also found that the simple scaling relation did not hold over land in either the zonal averages (Fig. 1e) or at the local grid box (Fig. 1f) scale. In fact~~ We note that it ~~it~~ would have been a real surprise if the simple scaling relation, $\Delta(P\text{-}E) \propto P\text{-}E$, did hold anywhere over land because that ~~such a~~ simple relation has never previously been identified in observations that span more than a century of hydrologic research (Blöschl et al., 2013).

To test an alternative approach to synthesise the model projections over land we found that the climate model projections ~~over land~~ closely follow the long-standing Budyko framework (Fig. 2). The Budyko curve emerged at both local grid box scales (Fig. 2e) and in zonal averages (Fig. 2f). This new result establishes that the climate model projections of $P\text{-}E$ and $\Delta(P\text{-}E)$ accord with more than a century of catchment research experience (Blöschl et al., 2013). It is also very useful because one can use differential forms of the Budyko framework (Roderick and Farquhar, 2011; also see Appendix A) to unravel the underlying basis of the projected response. The differential form introduced here is $\Delta(P\text{-}E) = \varepsilon_P\, \Delta P - \varepsilon_o\, \Delta E_o$ where the sensitivity terms (ε_P, ε_o) are calculated as a function of the existing climate (P, E_o) with E_o defined as the evaporative equivalent of the net irradiance. This approach accounts for most of the variation in the model projections (Figs 3e, 3f, 4). Further analysis showed that ~~,~~ most of the variation in $\Delta(P\text{-}E)$ was actually due to the $\varepsilon_P\,\Delta P$ term (Fig. 4a). Here we used the ~~a~~ multi-model ensemble mean but we note that there are large differences in ΔP projections at the grid box scale between different models, and, sometimes, between different runs of the same model (Lim and Roderick, 2009). It is for this reason that local (grid box) scale rainfall projections show the largest between-model differences of all hydro-climatic variables (Johnson and Sharma, 2009). Hence, while the grid box scale projections for P may be highly uncertain, the results presented here show that the ~~climate~~ multi-model ensemble mean does in fact partition local P between E and runoff in a manner consistent with experience. Whether the output from each individual climate model follows the Budyko framework remains a topic for future research. Perhaps the Budyko framework used here may prove useful for rapidly identifying individual climate models with poorly performing surface water and energy balance schemes.

Our results show that the "wet get wetter dry get drier" idea does not hold in terms of projected changes in the mean annual water balance over land (Fig. 1). Instead a rough rule of thumb for the land surface that can adequately account for climate model projections is $\Delta(P\text{-}E) \sim \varepsilon_P\,\Delta P$ with the sensitivity term (ε_P) varying from near unity in wet regions where $P\text{-}E$ is relatively large to near zero in dry regions where $P\text{-}E \to 0$ (Fig. 3, also see Appendix A). In the simplest possible terms our results show that when wet and dry are defined by $P\text{-}E$, the dry regions are projected to remain dry while wet regions could become either wetter or drier depending on any change in P. That result is also clearly evident in earlier maps for the land surface (see Fig. 6 in Held and Soden, 2006). It is straightforward to calculate ε_P from existing climatic data and the grand challenge is to estimate ΔP.

Our analysis was set in terms of the mean annual water balance and does not contain any information on the intra-annual (e.g. seasonal) variations that are so important from a variety of perspectives. Recent findings using the CMIP5 archive have been used to argue that the wet get wetter dry get drier idea holds for intra-annual (i.e., seasonal) variations in climate model projections out to the year 2100 (Kumar et al., 2014). That study used the same multi-model ensemble mean approach as we have and reported that at a given place, $P\text{-}E$ is projected to increase at wet times of the year but is projected to decrease during dry times of

Formatted: Font: Italic
Formatted: Font: Italic
Formatted: Font: Italic
Formatted: Font: Italic
Formatted: Font: Italic
Formatted: Font: Italic
Formatted: Font: Italic
Formatted: Not Superscript/ Subscript
Formatted: Font: Not Italic
Formatted: Font: Italic
Formatted: Font: Italic

the year (Kumar et al., 2014). Those conclusions relate specifically to intra-annual (i.e., seasonal) differences. One obvious conclusion from the Kumar et al. (2014) finding is that one would project the base flow to decrease whilst the high flows should increase. When integrated over the land surface and over a full year, the increases in high flow ~~must~~would have to be larger than the decreases in low flow so that the long term mean annual runoff ~~can~~could still increase to maintain an overall ~~mass balance~~increase in *P-E* over land (Table 1). In contrast, observations of the intra-annual streamflow from the United States for the second half of the 20th century show important regional variations but the overall trend tends to be the opposite of the above-noted model projections with increases in base flow and little change in high flows and an associated reduction in the extremes being reported (Lins and Slack, 1999; Lins and Slack, 2005). One important point to keep in mind is that real (as opposed to modelled) streamflows are subject to human modifications (e.g., extraction for irrigation, reservoir storage/release, etc.) that are not yet routinely included in global climate models. In that respect we note that at local and regional scales it is already clear that effects of human modifications in many river basins (Grafton et al., 2013) are substantially larger than ~~any~~those of the projected climate changes.

Returning to the model projections, w~~W~~e expected, and found, that the perturbed evaporative term ($\varepsilon_o\,\Delta E_o$) would show little spatial variation (Fig. 3d) in line with a global forcing induced by well mixed greenhouse gases. However, after 100 years the perturbation ($\varepsilon_o\,\Delta E_o$) remained small with an average over all land of only around 10 mm a^{-1} (Fig. 4b). The relevant sensitivity (ε_o) is more or less equal to the runoff ratio (= (*P-E*)/*P*, see Appendix A). That ratio is bounded and varies from near zero in very arid regions to near 1.0 ~~varies spatially and is typically around 0.2 (or less) in very arid regions but can be as high as 0.8~~ in wet humid regions (Fig. 3b, also see Appendix A). Even with that variation in ε_o accounted for, it is clear that the projected changes in ΔE_o were also typically small (Fig. 3d) with a global average of only +47 mm a^{-1}. Why is ΔE_o so small? To address that question we summarised all terms of the surface energy balance (Table 2, Fig. 5).

Our summary of projected changes in the global surface energy balance revealed several key points. The fact that the projected increase in global evaporation over land is smaller than the

Formatted: Font: Italic
Formatted: Font: Italic
Formatted: Superscript
Formatted: Font: Italic
Formatted: Font: Italic
Formatted: Font: Italic
Formatted: Font: Not Italic

increase over the ocean has been noted previously (Nohara et al., 2006; Richter and Xie, 2008). Over land, the evaporation increase is relatively small and the increase in incoming longwave irradiance is mostly partitioned into outgoing longwave irradiance that is physically related to the projected increase in surface temperature. Hence it is the smaller increase of *E* over land relative to the ocean that is a major factor permitting the land to warm faster than the ocean in the model projections (Boer, 1993; Sutton et al., 2007).

We took the energy balance ~~at~~ analysis one step further than is usual by separating the radiative terms into the respective incoming and outgoing shortwave and longwave components. That approach clearly revealed the underlying basis of the projected warming that occurs in the climate models. ~~ensemble.~~ In particular a relatively small top of the atmosphere forcing due to CO_2 and other long-lived greenhouse gases is amplified, mostly by water vapour feedback, into a large increase in the incoming longwave irradiance at the surface (Held and Soden, 2000, Russell et al., 2013). Paradoxically, there is not yet enough warming to be able to confidently test the projected changes against global observations of *P* and atmospheric water vapour (Liepert and Previdi, 2009; Vonder Haar et al., 2012). In that respect, ongoing monitoring of *P*~~,~~ and especially the atmospheric water vapour remain central. However, the results presented here (Fig. 5) suggest~~s~~ that monitoring the incoming longwave irradiance ~~, and especially of the incoming longwave irradiance~~ at the surface (Philipona et al., 2009; Philipona and Durr, 2004; Philipona et al., 2004; Philipona et al., 2005) should perhaps have the highest priority. ~~are the highest priority.~~

What is not so well known, yet critical for understanding the impacts on water availability, is that most (81%) of the realised surface forcing is partitioned into the outgoing longwave irradiance that is in turn physically related to the increase in surface temperature. Only a small fraction of the realised surface forcing (19%) enhances the latent heat flux with further small and more or less residual changes in other parts of the surface energy balance (Fig. 5). Because of that, the global sensitivity of *P* (e.g., 1.6% K^{-1}) can be used to calculate the flux partitioning (81%, 19%). This comes about because in that ratio (1.6% K^{-1}), the numerator gives the change in global *P* (and hence *E*) (1.6%) whilst the denominator (K^{-1}) gives the associated change in the outgoing longwave irradiance. When put into energetic units the sum of the numerator and denominator give the realised surface forcing. This new integrative framework shows that if the hydrologic cycle were to go faster, say at 7% K^{-1} (e.g., Wentz et al., 2007), then the increase in surface temperature would be smaller for a given realised surface forcing (Fig. 6).

Much ~~Most~~ public understanding of the impacts of climate change on water availability has been based on a ~~is based on the~~ conception that an increase in T leads to a faster hydrologic cycle in the sense that the global average E (and hence P) increase because the temperature increases. That conception ~~That perception~~ is partly true but it is ~~is~~ misleading because it is not the whole story. The key point is that E depends on more many more factors (e.g., humidity, wind, radiation, etc.) than just the surface T (Monteith, 1981). ~~A reinterpretation using the energy balance approach leads to the physically-based interpretation that for a given realised surface forcing, the greater the enhancement of global *E* (and hence *P*), the less the surface temperature increase (and vice versa).~~ From the point of view of communicating results to other scientists and to the impacts community one can avoid (or at least minimise) confusion by using the conservation of energy as a starting point. That leads directly to the notion that the greater the increase of E, the less the surface temperature increases (and vice versa).

Formatted: Font: Italic

Formatted: Font: Italic

Formatted: Normal

Acknowledgements

Parts of this research were first presented in the Dooge Memorial Lectures at the European Geosciences Union Annual Meeting in 2011. We acknowledge Jim Dooge's work as the inspiration for this research. We also acknowledge the modeling groups, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) and the WCRP'sWorking Group on Coupled Modeling (WGCM) for their roles in making available the WCRP CMIP3 multi-model dataset. Support of this dataset is provided by the Office of Science, U.S. Department of Energy. This research was supported by the Australian Research Council (CE11E0098).

References

Allen, M. R., and Ingram, W. J.: Constraints on future changes in climate and the hydrologic cycle, Nature, 419, 224-232, 2002.

Arora, V. K.: The use of the aridity index to assess climate change effect on annual runoff, Journal of Hydrology, 265, 164-177, 2002.

Arrhenius, S.: On the influence of carbonic acid in the air upon the temperature of the ground, Philosophical Magazine, 41, 237-276, 1896.

Boer, G. J.: Climate change and the regulation of the surface moisture and energy budgets, Climate Dynamics, 8, 225-239, 1993.

Budyko, M. I.: Evaporation under natural conditions, Israel Program for Scientific Translations, Jerusalem, 1948.

Budyko, M. I.: Climate and Life, Academic Press, New York, 508 pp., 1974.

Budyko, M. I.: The Earth's Climate: Past and Future, Academic Press, New York, 307 pp., 1982.

Choudhury, B. J.: Evaluation of an empirical equation for annual evaporation using field observations and results from a biophysical model, Journal of Hydrology, 216, 99-110, 1999.

de Groen, M.M. and Savenije, H.H.G., 2006. A monthly interception equation based on the statistical characteristics of daily rainfall. Water Resources Research, 42(12): W12417.

Donohue, R. J., Roderick, M. L., and McVicar, T. R.: On the importance of including vegetation dynamics in Budyko's hydrological model, Hydrology and Earth System Sciences, 11, 983-995, 2007.

Donohue, R. J., Roderick, M. L., and McVicar, T. R.: Assessing the differences in sensitivities of runoff to changes in climatic conditions across a large basin, Journal of Hydrology, 406, 234-244, 2011.

Donohue, R. J., Roderick, M. L., and McVicar, T. R.: Roots, storms and soil pores: Incorporating key ecohydrological processes into Budyko’s hydrological model, Journal of Hydrology, 436–437, 35-50, 2012.

Dooge, J. C. I., Bruen, M., and Parmentier, B.: A simple model for estimating the sensitivity of runoff to long-term changes in precipitation without a change in vegetation, Advances in Water Resources, 23, 153-163, 1999.

Durack, P. J., Wijffels, S. E., and Matear, R. J.: Ocean salinities reveal strong global water cycle intensification during 1950 to 2000, Science, 336, 455-458, 2012.

Fu, B. P.: On the calculation of the evaporation from land surface (in Chinese), Scienta Atmospherica Sinica, 5, 23-31, 1981.

Gerrits, A. M. J., Savenije, H. H. G., Veling, E. J. M., and Pfister, L.: Analytical derivation of the Budyko curve based on rainfall characteristics and a simple evaporation model, Water Resources Research, 45, W04403, 2009.

Grafton, R.Q. et al., 2013. Global insights into water resources, climate change and governance. Nature Clim. Change, 3(4): 315-321.

Formatted: Font: Times New Roman, 12 pt, English (U.K.)

Formatted: Font: Times New Roman, 12 pt, English (U.K.)

Formatted: Normal

Formatted: Font: Times New Roman, 12 pt, English (U.K.)

Held, I. M., and Soden, B. J.: Water vapour feedback and global warming, Annual Review of Energy and Environment, 25, 441-475, 2000.

Held, I. M., and Soden, B. J.: Robust responses of the hydrological cycle to global warming, Journal of Climate, 19, 5686-5699, 2006.

IPCC: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L., Cambridge University Press, Cambridge, UK and New York, USA, 2007.

Johnson, F., and Sharma, A.: Measurement of GCM skill in predicting variables relevant for hydroclimatological assessments, Journal of Climate, 22, 4373–4382, 2009.

Koster, R. D., and Suarez, M. J.: A simple framework for examining the interannual variability of land surface moisture fluxes, Journal of Climate, 12, 1911-1917, 1999.

~~Koster, R. D., Fekete, B. M., Huffman, G. J., and Stackhouse Jr., P. W.: Revisiting a hydrological analysis framework with International Satellite Land Surface Climatology Project Initiative 2 rainfall, net radiation, and runoff fields, Journal of Geophysical Research, 111, D22S05, 2006.~~

Kumar, S., Lawrence, D. M., Dirmeyer, P. A., and Sheffield, J.: Less reliable water availability in the 21st century climate projections, Earth's Future, n/a-n/a, 10.1002/2013ef000159, 2014.

Levitus, S., Antonov, J., and Boyer, T.: Warming of the world ocean, 1955–2003, Geophsyical Research Letters, 32, L02604, 2005.

Liepert, B. G., and Previdi, M.: Do models and observations disagree on the rainfall response to global warming?, Journal of Climate, 22, 3156-3166, 2009.

Lim, W. H., and Roderick, M. L.: An Atlas of the Global Water Cycle: Based on the IPCC AR4 models, ANU e-Press, Canberra, 293 pp., 2009.

Lins, H.F. and Slack, J.R., 1999. Streamflow trends in the United States. Geophysical Research Letters, 26: 227-230.

Lins, H.F. and Slack, J.R., 2005. Seasonal and Regional Characteristics of U.S. Streamflow Trends in the United States from 1940 to 1999. Physical Geography, 26(6): 489-501.

Meehl, G. A., T.F. Stocker, W.D. Collins, P. Friedlingstein, A.T. Gaye, J.M. Gregory, A. Kitoh, R. Knutti, J.M. Murphy, A. Noda, S.C.B. Raper, I.G. Watterson, Weaver, A. J., and Zhao, Z.-C.: Global Climate Projections, in: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller, Cambridge University Press, Cambridge, UK and New York, USA., 2007.

Mezentsev, V. S.: More on the calculation of average total evaporation, Meteorol. Gidrol., 5, 24-26, 1955.

Milly, P. C. D.: Climate, soil water storage, and the average annual water balance, Water Resources Research, 30, 2143-2156, 1994.

Monteith, J. L.: Evaporation and surface temperature, Quarterly Journal of the Royal Meteorological Society, 107, 1-27, 1981.

Formatted: Font: Times New Roman, 12 pt, English (U.K.)

Formatted: Font: Times New Roman, 12 pt, English (U.K.)

Nohara, D., Kitoh, A., Hosaka, M., and Oki, T.: Impact of climate change on river discharge projected by mutilmodel ensemble, Journal of Hydrometeorology, 7, 1076-1089, 2006.

O'Gorman, P. A., and Schneider, T.: The physical basis for increases in precipitation extremes in simulations of 21st-century climate change, Proceedings of the National Academy of Sciences, 10.1073/pnas.0907610106, 2009.

Oki, T., and Kanae, S.: Global hydrological cycles and world water resources, Science, 313, 1068-1072, 2006.

Paltridge, G., Arking, A., and Pook, M.: Trends in middle- and upper-level tropospheric humidity from NCEP reanalysis data, Theoretical and Applied Climatology, 98, 351-359, 2009.

Philipona, R., and Durr, B.: Greenhouse forcing outweighs decreasing solar radiation driving rapid temperature rise over land, Geophysical Research Letters, 31, 1-4, 2004.

Philipona, R., Durr, B., Marty, C., Ohmura, A., and Wild, M.: Radiative forcing - measured at Earth's surface - corroborate the increasing greenhouse effect, Geophysical Research Letters, 31, L03202, doi: 01029/02003GL018765, 2004.

Philipona, R., Durr, B., Ohmura, A., and Ruckstuhl, C.: Anthropogenic greenhouse forcing and strong water vapor feedback increase temperature in Europe, Geophysical Research Letters, 32, doi: 10.1029/2005GL023624, 2005.

Philipona, R., Behrens, K., and Ruckstuhl, C.: How declining aerosols and rising greenhouse gases forced rapid warming in Europe since the 1980s, Geophysical Research Letters, 36, L02806, doi: 02810.01029/02008GL036350, 2009.

Pielke Sr, R. A.: Heat storage within the earth system, Bulletin of American Meteorological Society, 84, 331-335, 2003.

Pike, J. G.: The estimation of annual runoff from meteorological data in a tropical climate, Journal of Hydrology, 2, 116-123, 1964.

Ramanathan, V., and Vogelmann, A. M.: Greenhouse effect, atmospheric solar absorption and the earth's radiation budget: From the Arrhenius-Langley era to the 1990's, Ambio, 26, 38-46, 1997.

Renner, M., and Bernhofer, C.: Applying simple water-energy balance frameworks to predict the climate sensitivity of streamflow over the continental United States, Hydrology and Earth System Sciences, 16, 2531-2546, 2012.

Richter, I., and Xie, S.-P.: Muted precipitation increase in global warming simulations: A surface evaporation perspective, J. Geophys. Res., 113, 2008.

Roderick, M. L., and Farquhar, G. D.: A simple framework for relating variations in runoff to variations in climatic conditions and catchment properties, Water Resour. Res., 47, W00G07, 2011.

Roderick, M. L., Sun, F., and Farquhar, G. D.: Water cycle varies over land and sea, Science, 336, 1230-1231, 2012.

Russell, G. L., Lacis, A. A., Rind, D. H., Colose, C., and Opstbaum, R. F.: Fast atmosphere–ocean model runs with large changes in CO_2, Geophysical Research Letters, 2013GL056755, 10.1002/2013gl056755, 2013.

Savenije, H., 2014. Review Comment. Hydrol. Earth Syst. Sci. Discussions, 10: C7524-C7527.

Sherwood, S. C., Roca, R., Weckwerth, T. M., and Andronova, N. G.: Tropospheric water vapor, convection, and climate, Reviews of Geophysics, 48, RG2001, 2010.

Sutton, R. T., Dong, B., and Gregory, J. M.: Land/sea warming ratio in response to climate change: IPCC AR4 model results and comparison with observations, Geophysical Research Letters, 34, L02701, 2007.

Trenberth, K. E., Fasullo, J. T., and Kiehl, J. T.: Earth's global energy budget, Bulletin of the American Meteorological Society, 90, 311-323, 2009.

Turc, L.: Le bilan d'eau des sols. Relation entre les precipitations, l',evaporation et l'ecoulement, Annals of Agronomy, 5, 491-569, 1954.

Vonder Haar, T. H., Bytheway, J. L., and Forsythe, J. M.: Weather and climate analyses using improved global water vapor observations, Geophysical Research Letters, 39, L15802, 10.1029/2012gl052094, 2012.

Wentz, F. J., Ricciardulli, L., Hilburn, K., and Mears, C.: How much more rain will global warming bring?, Science, 317, 233-235, 2007.

Wild, M., Folini, D., Schär, C., Loeb, N., Dutton, E., and König-Langlo, G.: The global energy balance from a surface perspective, Climate Dynamics, 40, 3107-3134, 2013.

Wu, P., Christidis, N., and Stott, P.: Anthropogenic impact on Earth's hydrological cycle, Nature Clim. Change, 3, 807-810, 2013.

Yang, D., Sun, F., Liu, Z., Cong, Z., Ni, G., and Lei, Z.: Analyzing spatial and temporal variability of annual water-energy balance in nonhumid regions of China using the Budyko hypothesis, Water Resources Research, 43, W04426, 2007.

Yang, H., Yang, D., Lei, Z., and Sun, F.: New analytical derivation of the mean annual water-energy balance equation, Water Resources Research, 44, W03410, doi:03410.01029/02007WR006135, 2008.

Zhang, L., Dawes, W. R., and Walker, G. R.: Response of mean annual evapotranspiration to vegetation changes at catchment scale, Water Resources Research, 37, 701-708, 2001.

Formatted: English (U.K.), Do not check spelling or grammar

Appendix A

Derivation of alternative sensitivity coefficients by Prof H. Savenije

While this paper was under review, the journal editor presented an alternative derivation of the sensitivity coefficients (i.e., alternative to Eq. 2-4 in main text) based on an alternative mathematical form of the Budyko curve (de Groen and Savenije, 2006; Gerrits et al., 2009). The new derivation was novel and offered advantages for the physical interpretation of the sensitivity coefficients (Savenije, 2014). An onverview of this new derivation due to Prof Savenije is presented here to aid in the physical interpretation of the sensitivity coefficients $(\varepsilon_P, \varepsilon_o)$ in the main text.

The form of the Budyko curve we used is (see Eq. 1 in main text) ,

$$E = \frac{P\,E_o}{\left(P^n + E_o^n\right)^{1/n}} \qquad \text{(A1)}$$

In the review of our article, Prof Savenije began with the Schreiber form of the Budyko curve,

$$E = P\left(1 - e^{-\left[\frac{E_o}{P}\right]}\right) \qquad \text{(A2)}$$

Note that Eq. (A2) reproduces the climate model output (Fig. 7). This implies that Eq. (A2) is more or less numerically identical to Eq. (A1) when *n* = 1.5 (see Fig. 2 caption).

Figure 7 here

Numerically either equation is an adequate description for our purpose. Eq. (A1) has the advantage that the adjustable parameter, *n*, can be varied to describe real catchments (see discussion in main text). Eq. (A2) has the advantage that the sensitivity coefficients take a particularly simple form. To see that, we start with Eq. (4) from the main text,

$$d(P-E) = \left(1 - \frac{\partial E}{\partial P}\right) dP - \frac{\partial E}{\partial E_o}\, dE_o = \varepsilon_P\, dP - \varepsilon_o\, dE_o \qquad \text{(A3)}$$

Calculating the sensitivity coefficients using Eq. (A2) we get,

Formatted: Font: Bold

Formatted: Font: Bold

Formatted: Line spacing: 1.5 lines

Field Code Changed

Formatted: Indent: First line: 0"

Field Code Changed

Formatted: Line spacing: 1.5 lines

Field Code Changed

Formatted: Font: Italic

Formatted: Font: Italic

Field Code Changed

$$\frac{\partial E}{\partial P}=\frac{-E_o}{P}e^{-\frac{E_o}{P}}-e^{-\frac{E_o}{P}}+1 \quad , \qquad \text{(A4)}$$

and after some rearrangement and simplification we find,

$$\varepsilon_P=1-\frac{\partial E}{\partial P}=\left(\frac{P-E}{P}\right)\left(\frac{E_o}{P}+1\right) \quad . \qquad \text{(A5)}$$

Similarly,

$$\varepsilon_o=\frac{\partial E}{\partial E_o}=e^{-\frac{E_o}{P}}=\left(\frac{P-E}{P}\right) \quad . \qquad \text{(A6)}$$

Putting those two results into Eq. (A3) we have,

$$d(P-E)=\left(\frac{P-E}{P}\right)\left(\frac{E_o}{P}+1\right)\ dP-\left(\frac{P-E}{P}\right)dE_o \quad . \qquad \text{(A7)}$$

The advantages of this form for physical interpretation become very clear. First, we note that $(P-E)/P$ is simply the runoff ratio. In other words the sensitivity of *P-E* to variations in net irradiance (E_o) is determined by the runoff ratio. Secondly, E_o/P is known as the aridity index, Hence it is clear that the sensitivity of *P-E* to variations in *P* depends on the runoff ratio and an enhancement that depends on the aridity index.

We found that dE_o is generally small in the model projections (Fig. 3d). If we ignore those variations in this instance we have,

$$d(P-E)\approx\left(\frac{P-E}{P}\right)\left(\frac{E_o}{P}+1\right)\ dP \sim \quad , \qquad \text{(A8)}$$

as a simple form that provides physical guidance to the interpretation.

Field Code Changed

Field Code Changed

Field Code Changed

Field Code Changed

Formatted: Font: Italic

Formatted: Font: Italic

Formatted: Font: Italic

Formatted: Subscript

Formatted: Font: Italic

Formatted: Subscript

Formatted: Font: Italic

Formatted: Font: Italic

Formatted: Font: Italic

Formatted: Font: Italic

Formatted: Font: Italic

Formatted: Subscript

Field Code Changed

Table 1 Mean annual water balance over the globe, ocean and land simulated at the end of the 20^{th} century (1970-1999, 20C3M) and the changes projected to the end of the 21^{st} century (2070-2099, A1B). The percentages are shown below the projected changes. Note that the change in global mean surface temperature between the two periods is +2.8 K, giving a projected change in global *P* (and *E*) of (4.5% / 2.8 K =) 1.6% K^{-1}.

Formatted: Normal

Region	**Area**	**1970-1999 (20C3M)**			**2070-2099 (A1B)**		
		P	E	P-E	ΔP	ΔE	$\Delta(P\text{-}E)$
	($\times 10^{14}$ m^2)	(mm a^{-1})			(mm a^{-1})		
GLOBE	5.09	1045	1045	0	47	47	0
					[4.5%]	[4.5%]	[0%]
OCEAN	3.62	1153	1248	-95	50	58	-8
					[4.3%]	[4.7%]	[8.4%]
LAND	1.47	775	542	+233	41	20	+21
					[5.3%]	[3.7%]	[9.0%]

Table 2 Surface energy balance components for the globe, ocean and land simulated at the end of the 20th century (1970-1999, 20C3M) and projected to the end of the 21st century (2070-2099, A1B). Areas (globe, ocean, land) are listed in Table 1. *T*, surface temperature; $R_{S,i}$, incoming shortwave irradiance; $R_{S,o}$, outgoing shortwave irradiance; $R_{L,i}$, incoming longwave irradiance; $R_{L,o}$, outgoing longwave irradiance; R_N (= $R_{S,i}$ - $R_{S,o}$ + $R_{L,i}$ - $R_{L,o}$), net irradiance; *LE*, latent heat flux; *H*, sensible heat flux; *G*, rate of change in enthalpy~~storage~~.

Region	Period	*T* (°C)	$R_{S,i}$ (W m^{-2})	$R_{S,o}$ (W m^{-2})	$R_{L,i}$ (W m^{-2})	$R_{L,o}$ (W m^{-2})	R_N (W m^{-2})	*LE* (W m^{-2})	*H* (W m^{-2})	*G* (W m^{-2})
GLOBE	1970-1999	13.6	185.8	25.5	335.2	392.0	103.5	82.3	20.0	1.3
	2070-2099	16.4	184.1	23.8	353.8	406.8	107.3	86.0	18.9	2.4
	Δ	**2.8**	**-1.7**	**-1.7**	**18.6**	**14.8**	**3.8**	**3.7**	**-1.1**	**1.1**
OCEAN	1970-1999	15.8	183.6	16.2	349.3	402.1	114.7	98.3	15.2	1.2
	2070-2099	18.2	181.8	14.8	366.6	414.9	118.7	102.9	13.2	2.7
	Δ	**2.4**	**-1.8**	**-1.4**	**17.3**	**12.8**	**4.0**	**4.6**	**-2.0**	**1.5**
LAND	1970-1999	8.3	191.3	48.4	300.4	367.2	76.0	42.7	31.8	1.5
	2070-2099	12.1	189.8	46.1	322.1	386.8	79.0	44.3	33.1	1.6
	Δ	**3.8**	**-1.5**	**-2.3**	**21.7**	**19.6**	**3.0**	**1.6**	**1.3**	**0.1**

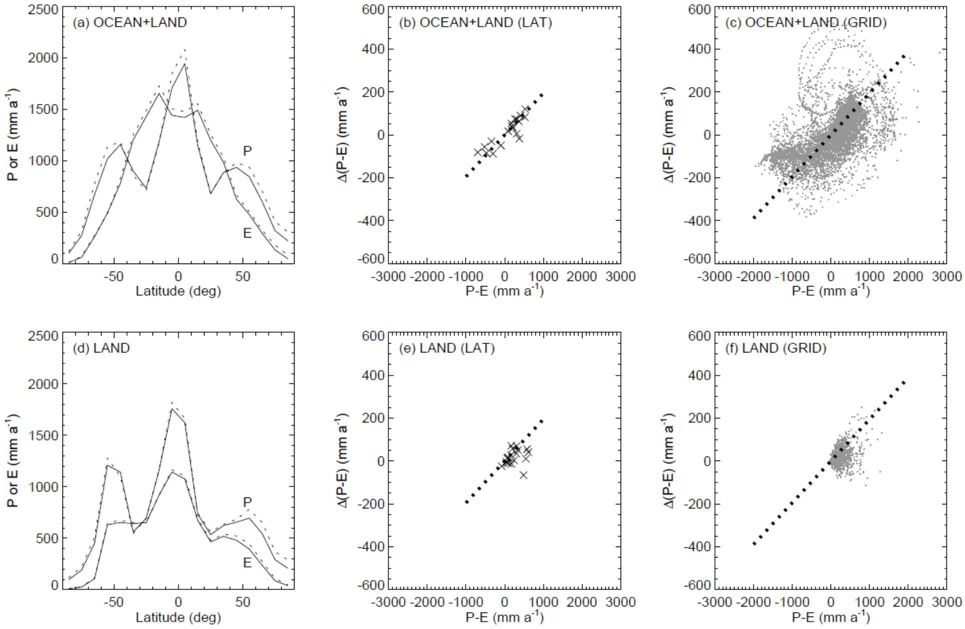


Figure 1 Annual average *P* and *E* over the (top panels) globe (land plus ocean) and over (bottom panels) land. (a) Latitudinal distribution of *P*, *E* at the end of the 20th (1970-1999, 20C3M) (full) and 21st (2070-2099, A1B) (dotted) centuries. (b) $\Delta(P\text{-}E)$ versus $P–E$ averaged over 10° latitudinal zones. (c) $\Delta(P\text{-}E)$ versus $P–E$ at individual grid boxes. (d) (e) (f) Equivalent plots restricted to the land component. Dotted line (b) (c) (e) (f) highlights the Held and Soden (2006) prediction ($\Delta(P\text{-}E) = 0.07\ K^{-1} \times 2.8\ K \times (P\text{-}E) = 0.20 \times (P\text{-}E)$) for the projected increase in global mean temperature.

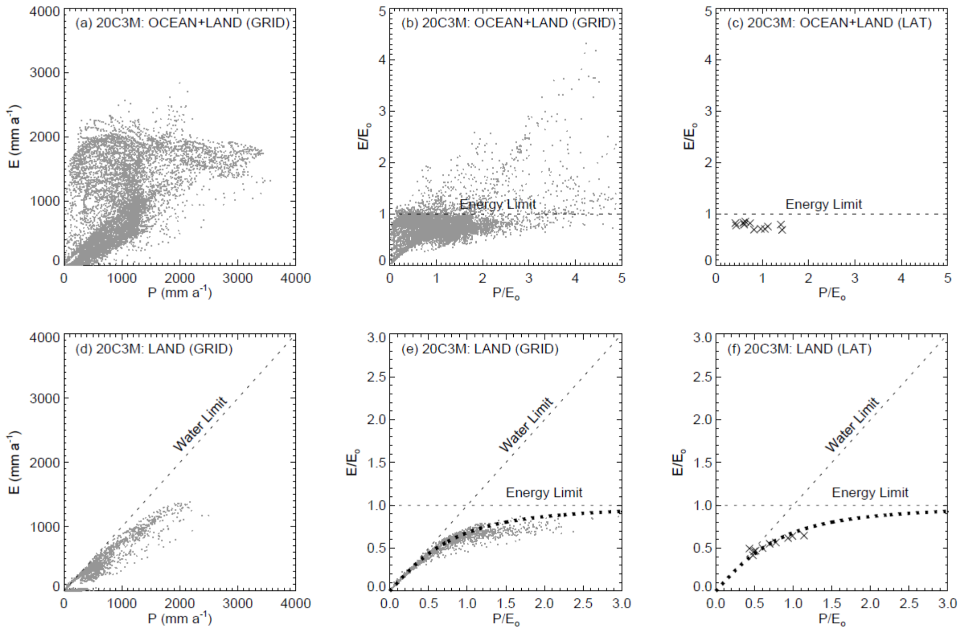


Figure 2 Relation between mean annual P and E over the (top panels) globe (land plus ocean) and over (bottom panels) land. All climate model output are for the end of the 20th century (1970-1999). Model output for (a) P, E at individual grid boxes (b) normalised by the net irradiance (E_o), and (c) averaged over 10° latitudinal zones. (d) (e) (f) Equivalent plots restricted to the land component. The energy ($E/E_o = 1$) and water ($E \leq P$) limits are discussed in the main text. The dotted curve in panels (e) and (f) is the predicted Budyko curve (Eq.~~n~~ 1) with the default value of the parameter (n = 1.8, Choudhury (1999)). (Note: in (e) a better fit is obtained using n = 1.5 but adopting that value does not materially change the subsequent results or conclusions.)

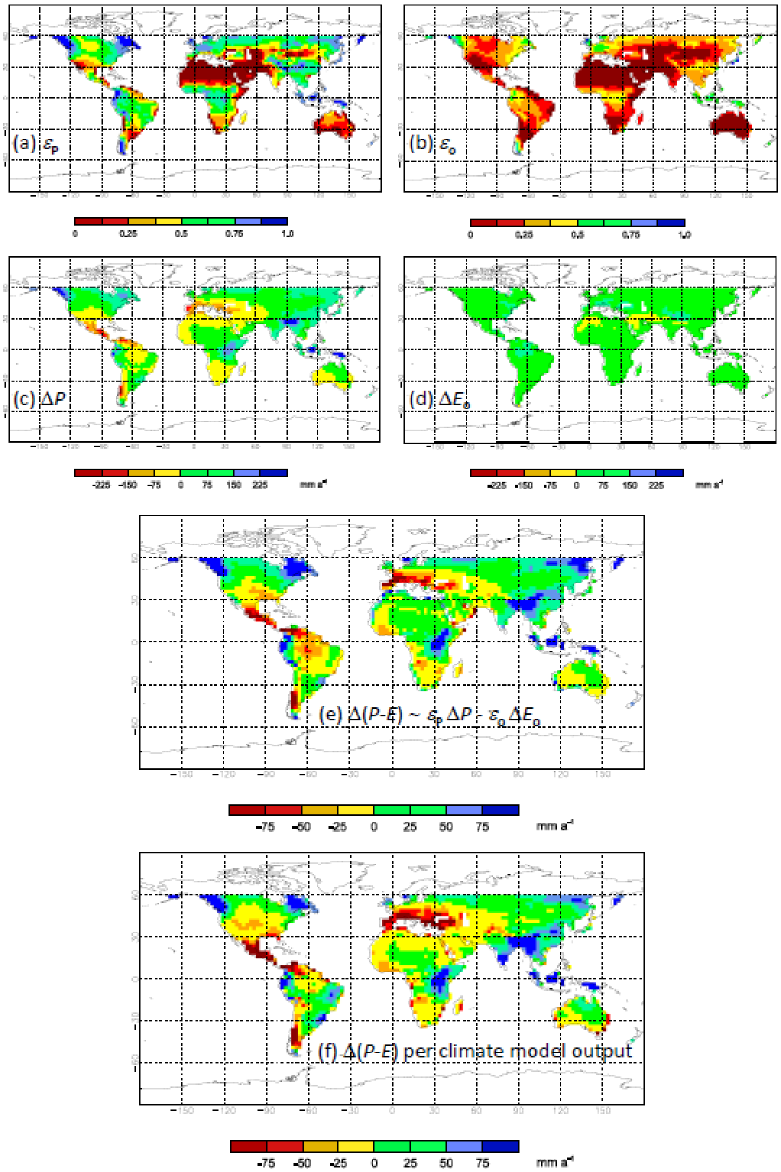


Figure 3 Comparison of $\Delta(P\text{-}E)$ estimated using the Budyko-based framework versus $\Delta(P\text{-}E)$ calculated from climate model output. Components of the Budyko-based approach include (a) ε_P (Eq.~~n~~ 4) (b) ε_o (Eq.~~n~~ 4) (c) ΔP (per climate model output), (d) ΔE_o (per climate model output) and the (e) calculated change, $\Delta(P\text{-}E) \sim \varepsilon_P \Delta P - \varepsilon_o \Delta E_o$ (Eq. ~~n~~ 4) compared with (f) $\Delta(P\text{-}E)$ calculated directly from the climate model output.

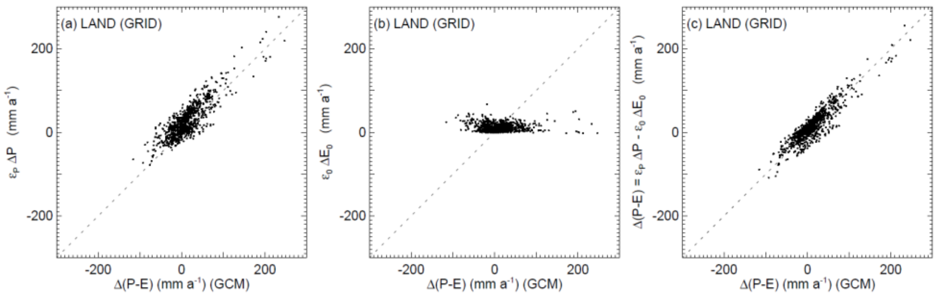


Figure 4 Comparison between components of the change predicted by the theory with changes projected by the global climate multi-model ensemble mean (GCM). Change in ~~Δ(~~P-E~~)~~ due to change in (a) the rainfall ($\varepsilon_P\,\Delta P$) (regression: y = 0.89 x + 13.8, R^2 = 0.72, N=1119) (b) the evaporative term ($\varepsilon_o\,\Delta E_o$) (regression: y = 0.01 x + 9.8, R^2 = 0.00, N=1119) and the (c) total calculated change ($\Delta(P\text{-}E) = \varepsilon_P\,\Delta P - \varepsilon_o\,\Delta E_o$) (regression: y = 0.89 x + 4.0, R^2 = 0.82, N=1119) versus the GCM estimates of Δ(P-E).

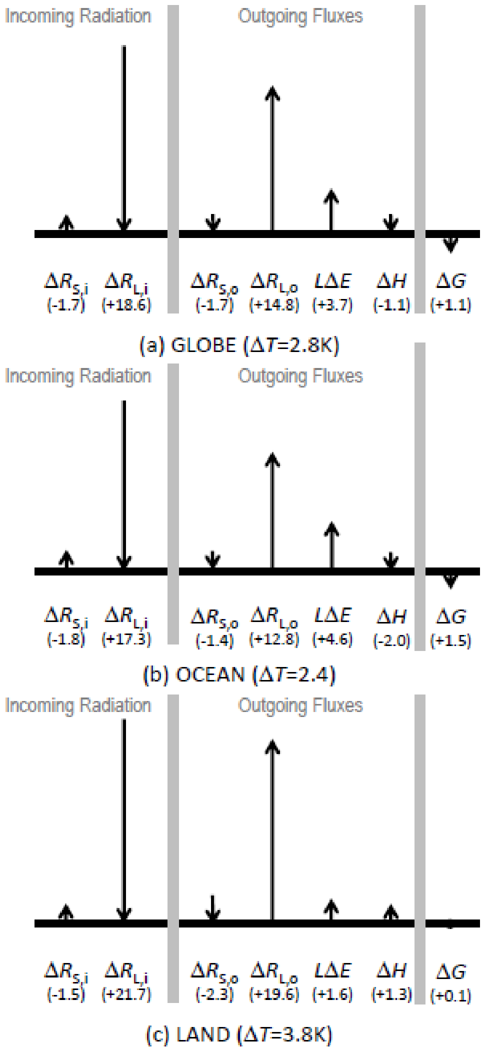


Figure 5 Stylised diagram showing projected changes (2070-2099 less 1970-1999) in components of the surface energy balance (units: W m^{-2}) over the (a) globe, (b) ocean and (c) land. Data are from Table 2. Projected changes in (left) incoming radiation (shortwave, $\Delta R_{S,i}$; longwave, $\Delta R_{L,i}$) are separated from (middle) changes in the outgoing radiative ($\Delta R_{S,o}$, $\Delta R_{L,o}$) and convective ($L\Delta E$, ΔH) fluxes and from (right) the rate of change in enthalpy ~~storage~~ (ΔG). ΔT (below each panel) denotes the surface temperature change.

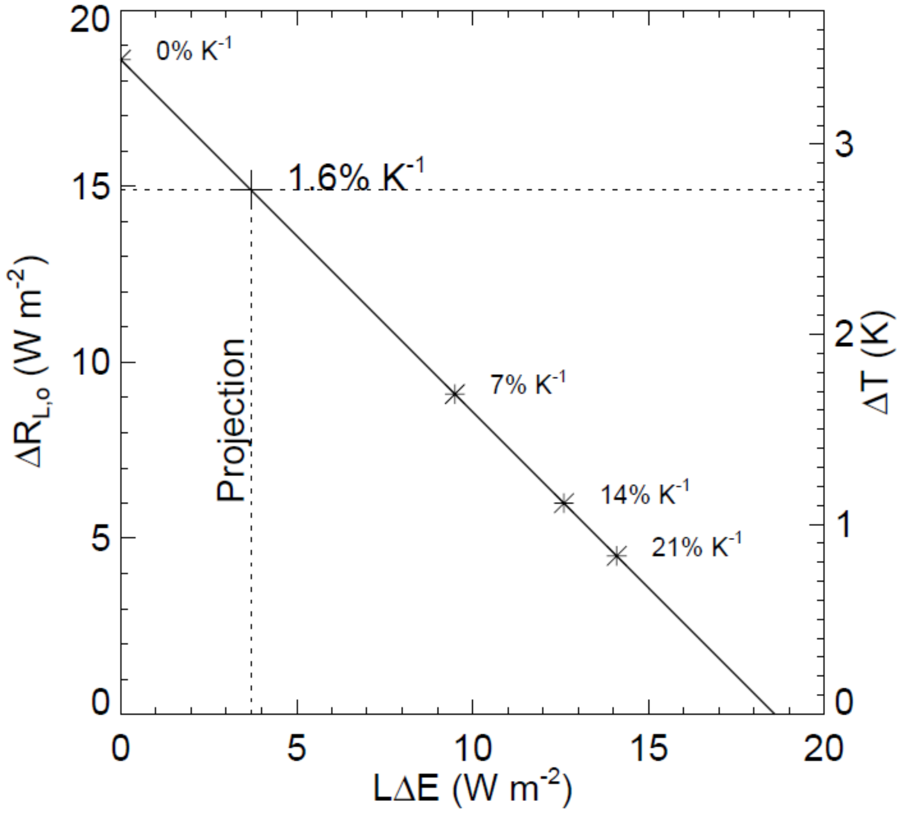


Figure 6 Relation between global projected change in ~~of~~ the latent heat flux ($L\Delta E$) and ~~the~~ outgoing longwave irradiance ($\Delta R_{L,o}$) for a given increase in incoming longwave irradiance ($\Delta R_{L,i} \approx \Delta R_{L,o} + L\Delta E = 18.6$ W m^{-2}). Equivalent surface temperature changes are noted (right-hand axis) as are the percentage enhancements in global P per Kelvin.

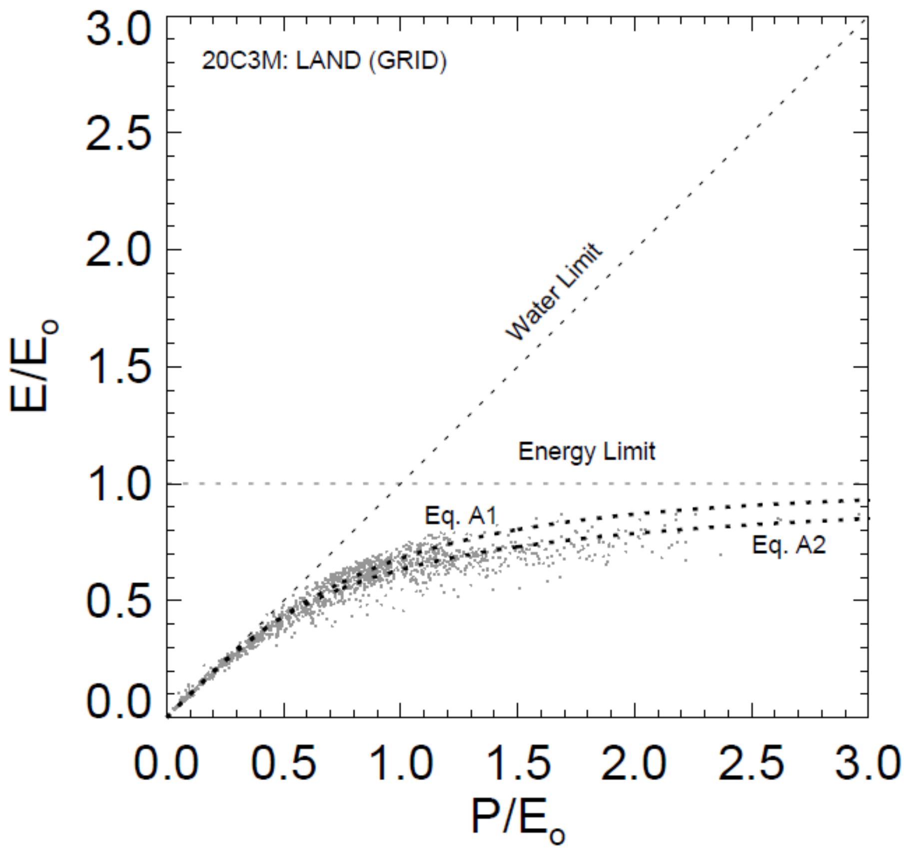


Figure 7 Comparison of the two alternate forms (Eq. A1 vs Eq. A2) of the Budyko curve. All else is the same as Fig. 2e in the main text.

Formatted: Line spacing: 1.5 lines