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Atmospheric Chemistry and Physics Discussions

Interactive comment on "Direct and disequilibrium effects on precipitation in transient climates" *by* D. McInerney and E. Moyer

R.P. Allan

r.p.allan@reading.ac.uk

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The authors make a valuable contribution to the discussion on physical mechanisms of transient precipitation (P) changes at the largest scales, particularly in considering the land and ocean responses separately and linking this to disequilibrium of the climate system. This extends recent advances (e.g. Allen and Ingram, 2002; Andrews et al. 2010), and I consider that the work should be published.

I found the article challenging (excuse any of my misunderstandings) and I have a number of comments, which were invited by the authors. In particular, some further clarification of the physical mechanisms outlined (and physical meaning of disequilibrium coefficients c1 and c2) with some consideration of moisture and energy fluxes between land and ocean would be welcome. I supply a short list of additional references that would be useful to consider, in particular the study by Cao et al. (2012) which is highly relevant.

1) Energetic constraints

My interpretation of Allen and Ingram (2002) is that eq(4) (p.19654, line 13) remains applicable (energy budget constraint) but that the "alpha" term is dependent upon the spatial distribution of surface temperature change (dT) which determines precisely how atmospheric radiative cooling responds to global warming. This is sensitive to the land/ocean warming contrast which is partly influenced by how far from equilibrium the climate system is (although feedbacks independent of disequilibrium also contribute, e.g. Lambert et al. 2011).

It would appear to me that both the Andrews and Forster (2010) and Wu et al. (2010) work (mentioned p. 19652, line 20) is compatible with eq(4) since in the CO2 ramp-up phase the radiative forcing increase is suppressing P (smaller global dP/dT) while in the ramp-down phase radiative forcing is diminishing yet T continues to rise due to time-scales associated with ocean heat uptake and radiative feedbacks (larger dP/dT). This is also discussed in O'Gorman et al. (2012).

2) Physical Mechanisms

I found the some of the descriptions of physical mechanisms rather confusing (e.g. p.19654, line 25-30). The effects of CO2/Solar forcing on rapid adjustments over land and ocean are well described by Cao et al. (2012) and it would be useful to refer to this analysis and consider horizontal fluxes of energy and moisture between land and ocean.

Given that land T rises more than ocean T in response to positive radiative forcings (even at equilibrium) this has implications for land dP/dT. The land minus ocean T influences circulation strength, certainly for monsoon systems (e.g. Levermann et al. 2009), while the ocean T sets the moisture burden destined for the land (through the

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Clausius Clapeyron equation). Outlining physical mechanisms for transient changes in this context may be useful in relation to p.19658-p.19659, including discussion of moisture and energy transport changes.

The physical basis for c1 and c2 (eq(3) and Fig. 5) may need further clarification. As far as I can tell, c1 seems to be the total dP_eq/dT_eq which, unlike the fast/slow framework, is dependent upon forcing agent which is not a beneficial property. If c2=-Beta_CO2/dT_eq, the difference in patterns shown in Fig. 7 are solely between c1 and alpha (the total dP_eq/dT_eq which is dependent on forcing type verses the slow temperature-dependent dP/dT response which is independent of forcing type but has a sensitivity to the pattern of dT which depends partly upon disequilibrium).

A surface energy perspective is presented by the authors in Section 6. Some clarification with regard to the physical mechanisms would be beneficial. For example, on line 1 it is stated that "In the CO2 forcing case, more than half of the initial heat uptake is accommodated by a reduction in latent heat and therefore precipitation." It is difficult to see how CO2 increases can directly increase evaporation since the immediate effect will be heating of the atmosphere. It is only be reduced P that water vapour may not be removed from the surface layers, thus inhibiting evaporation. Similarly, more evaporation does not simply lead to more P since the low level water vapour must be uplifted through some mechanism (thereby ventilating the surface) which requires additional radiative cooling of the atmosphere. I did not understand the comment on line 16, "the direct effect is opposite sign than that assumed by Andrews et al." The global response appears as predicted by the fast/slow framework; the land response requires rapid adjustments in moisture and energy fluxes between land and ocean (e.g. Cao et al. 2012).

The authors also argue that "increased solar forcing cannot produce a transient suppression of precipitation in the global average" (line 1 or p.19667). Radiative heating through absorption by water vapour and aerosols will heat the atmosphere (e.g. Andrews et al. 2010), suppressing precipitation initially over the ocean, before the T

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begins to rise (Cao et al. 2012). This is of course not the case over land where direct warming of the surface can occur. Increases in surface evaporation may only be sustained if that water can be removed from the near surface (through convective processes for example) requiring enhanced radiative cooling or removal of energy through lateral fluxes (e.g. inflow of cool ocean air, see Levermann et al. 2009). Consistent with the present study, however, the results from Cao et al. (2012) indeed suggest that the initial effect of increased solar radiative forcing is a global increase in P.

3) Regional Patterns

The regional P response (p.19662, line 20) are related to enhanced moisture fluxes from dry to wet regions (due to larger moisture burdens with warming) which act to enhance P-E patterns (e.g. Held and Soden 2006). Considering an energetic perspective has also been shown to be useful (e.g. Muller and O'Gorman 2011; Levermann et al. 2009 PNAS).

The anti-correlation between alpha and beta in Fig. 6 is interesting. But are the precipitation change patterns merely aliased onto these parameters? Again, If c2 is just equal to –Beta_CO2/dT_eq the pattern is essentially the same in Fig. 7b, 7d and Fig. 8b. c1 and c2 have the same units but alpha and beta_CO2 do not. The gradient of alpha and beta is about -1.5 K for CO2 and -1.25 K for Solar which I think shows the dT at which the "fast" and "slow" components exactly cancel.

4) Additional comments and clarifications

a) The altitude of instantaneous radiative forcing is also thought to be important. Ming et al. (2010) show that absorbing aerosol added to the boundary layer causes adjustments through sensible heat rather than latent heat which is governed by forcings above the lifting condensation level (e.g. O'Gorman et al. 2012).

b) Although it is true that people tend to live on land (e.g. p.19657), a large proportion of of the global population lives within 400km of the oceans so ocean changes and

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ocean-land transports are also important. Nevertheless I agree that understanding mechanisms for land and ocean responses is vital. Energetic constraints still apply regionally (accounting for lateral fluxes) as described by Muller and O'Gorman (2011).

c) Fig. 7: It would be helpful to increase the colour bar range to -30/+30 for Fig. 7a for consistency with Fig. 7b (to show that c1 is smaller in magnitude than c2).

d) Fig. 8a It may be worth noting that dP_eq is just c1*dT_eq so the pattern is essentially shown in Fig. 7a. Fig 8b: Is "Initial intercept" simply Beta_CO2 shown in Fig. 7d?

e) Fig. 9: The fluxes appear to be defined as upward, out of the surface, apart from the residual (which is the heat flux into the ocean) contrary to the caption. For example in the solar case there is an initial negative solar flux anomaly of 4 Wm-2 whereas the forcing is positive 4 Wm-2.

Typos:

p.19656, line 10, typo: "presumably the same"

p.19668, line 11 "all positive forcings"?

p.19668, line 18 "the pure fast/slow"

Fig. 3 caption, last line "appears to be acting"

Additional References:

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