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Direct and disequilibrium effects on precipitation in transient climates

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Abstract

Climate models are in broad agreement that global precipitation increases with surface temperature as atmospheric CO_2 concentrations rise, but recent studies have shown that climates that are not yet in equilibrium exhibit additional "transient precipitation effects". In conditions of rising CO_2, for example, precipitation at a given temperature is suppressed relative to its equilibrium value. Some authors argue that the primary driver of these effects is ocean heat uptake, but most recent studies assume that they result from some direct radiative effect. We show here that global precipitation and temperature anomalies are insufficient to resolve mechanisms, since the conventional "fast/slow" representation of transient precipitation effects is degenerate with a "disequilibrium" representation that posits control only by ocean heat uptake. We use regional anomalies instead to show in multiple ways that ocean heat uptake is the dominant driver of transient precipitation effects in CO_2-forced climates. Precipitation suppression appears predominantly over the ocean, with response over land of the opposite sign. The coefficients of a disequilibrium representation are uncorrelated, suggesting that they capture physically meaningful processes, while those of a fast/slow representation are highly correlated. Further, the regional patterns of transient precipitation response are highly similar for both CO_2 and solar forcing, with a relatively small and homogeneous offset between them. Examination of the surface energy budget allows us to conclude that energy balance in solar-forced climates is achieved by the superposition of both disequilibrium and direct processes. Our results highlight the importance of using regional information rather than global aggregates for understanding the physics of transient climate change and its impacts on societies.

1 Introduction

The several thousand year timescale of ocean turnover means that the climatic response to a given change in greenhouse gas concentrations is not fully manifested

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for millennia. The transient response of climate is therefore of interest not just to the scientific community but to society at large, as we are presently living in a transient climate. Determining impacts relevant to humans requires understanding not only the final equilibrium state under changed radiative forcing but also the pathway by which the climate approaches that equilibrium.

Numerous modeling studies have suggested that transient climates display particular responses in precipitation that are not simply proportional to temperature: in conditions of rising CO_2, precipitation change per unit warming is suppressed relative to its equilibrium value ($\Delta P/\Delta T < \Delta P_{eq}/\Delta T_{eq}$) (e.g. Dong et al., 2009; Andrews and Forster, 2010; Andrews et al., 2010; Bala et al., 2010; Lambert et al., 2011). These "transient precipitation effects" are robust enough across models that they must be taken seriously, as this climate behavior is likely occurring now. One consequence demonstrated in models is that after rising greenhouse gas concentrations are stabilized, but global temperature continues to slowly warm, precipitation will rise more strongly with temperature than it did pre-stabilization (Andrews and Forster, 2010). The physical implication is that precipitation in a warming or cooling climate is a function not only of temperature but also of the rate of change in radiative forcing.

Transient precipitation effects have several potential implications for human and ecosystem welfare. First, they complicate prediction of future climate impacts, since current observations of precipitation change per unit warming will underestimate long-term equilibrium values (Andrews and Forster, 2010). Second, they invalidate simplified climate prediction tools based on "pattern scaling" (Wu et al., 2010), which necessarily assume that changes in regional climate (local temperature, precipitation) are linear with changes in global mean temperature (Santer et al., 1990; Mitchell et al., 1999; Mitchell, 2003). Finally, if greenhouse gases are changed quickly, as would occur with sudden changes in methane emissions or in extreme CO_2 air capture scenarios, the abrupt imposition of a large negative forcing change can result in a short-term spike in precipitation, cited as potentially harmful to humans (Cao et al., 2011; Wu et al., 2010).

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In one of the earliest treatments of precipitation in transient climates, Allen and Ingram (2002) speculated that transient precipitation effects may be driven in part by a direct effect of radiative forcing (ΔR) associated with the specific forcing agent and in part by ocean heat uptake (N). The total change in precipitation (ΔP) would then be given by the intrinsic response to temperature change (ΔT), plus these transient modifications:

$$\Delta P = a\Delta T + b\Delta R + cN. \tag{1}$$

The ocean heat uptake effect could be interpreted as relating to transient cooling at the ocean surface that leads to differential warming with altitude. The ocean's thermal inertia means that if atmospheric CO_2 rises, the mid-troposphere initially warms more strongly than the surface, increasing atmospheric stability and thereby decreasing convection and precipitation. From a surface energy budget perspective, ocean heat uptake reduces the energy available for evaporation and hence precipitation. In the surface energy budget perspective, the direct effect would relate to changes in energy fluxes other than ocean heat uptake: longwave and shortwave radiation and sensible heat.

Allen and Ingram (2002) were unable to verify their proposed relationship, or to constrain its parameters, since the relationship between ΔP and ΔT in their multi-model dataset was too weak. Since that study, some authors have emphasized the importance of the ocean heat uptake term. Wu et al. (2010), for example, concluded from a surface energy budget analysis of scenarios where CO_2 was ramped up and down that ocean heat uptake was the main driver of transient effects (in their terms, "hydrological hysteresis"). Most recent studies have however assumed that the sole driver of transient precipitation effects is the direct term, i.e. a permanent effect driven by the forcing agent alone (e.g. Andrews and Forster, 2010; Cao et al., 2011).

It would seem that the two effects should be readily differentiated, since while the disequilibrium responses should decrease as the oceans slowly warm, and disappear when the Earth reaches its final equilibrium, any responses caused directly by radiative forcing will not evolve over time. However, resolving the cause of transient precipitation

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effects is made difficult because Allen and Ingram (2002)'s equation is degenerate in terms of the two observables ΔP and ΔT. To first order, ocean heat uptake is linearly proportional to climate disequilibrium ($\Delta T_{eq} - \Delta T$). (A zero-dimensional energy balance model implies that $N = R - \lambda \Delta T$ (Winton et al., 2010; Raper et al., 2002), where N is ocean heat uptake, R is radiative forcing, and λ is the feedback parameter that governs climate sensitivity to forcing changes. If λ is a constant of the climate system and forcing R is stabilized, then $\Delta T_{eq} = R/\lambda$ and $N = \lambda(\Delta T_{eq} - \Delta T)$.) This means that Allen and Ingram (2002)'s representation becomes (folding λ into the coefficients, and adjusting the sign of the heat uptake):

$$\Delta P = a\Delta T + b\Delta T_{eq} - c(\Delta T_{eq} - \Delta T). \tag{2}$$

which can be arranged equally well to suggest that transient precipitation is driven only by climate disequilibrium:

$$\Delta P = c_1 \Delta T - c_2(\Delta T_{eq} - \Delta T). \tag{3}$$

where $c_1 = (a + b)$ and $c_2 = (-b + c)$, or to suggest that the only driver is a direct effect of the forcing agent:

$$\Delta P = \alpha \Delta T + \beta \Delta T_{eq}, \tag{4}$$

where $\alpha = a + c$ and $\beta = (b - c)$.

The latter relationship is essentially that used by numerous authors in the recent literature though it may be expressed in a variety of ways. Since direct effects of changing radiative balance occur immediately, while temperature rises slowly as the climate equilibrates, the components of precipitation are often described as a "fast" and "slow" term, $\Delta P = \Delta P_{slow} + \Delta P_{fast}$, where the slow term is $\alpha \Delta T$ and the fast term $\beta \Delta T_{eq}$ (Andrews and Forster, 2010; Andrews et al., 2010; Cao et al., 2011). In the case of CO_2 forcing, the fast term can also be expressed as $\beta_{CO_2} \log_2 \left(CO_2/CO_{2,PI}\right)$ (Cao et al., 2011).

Throughout this paper we will refer to these end-member cases as pure "fast/slow" and "disequilibrium" responses. The true atmospheric response can of course lie anywhere on the spectrum of relative importance of these different mechanisms. While

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model data have been shown to fit the relationships above well (Andrews et al., 2010; Andrews and Forster, 2010; Cao et al., 2011), the degeneracy means that model fits cannot alone differentiate between possible physical drivers of transient precipitation effects.

One of the factors that has led many researchers to suggest that a direct forcing effect is the dominant cause of transient precipitation effects is the comparison between runs forced in different ways, e.g. by a change in infrared-absorbing CO_2 vs. a change in shortwave radiation from the sun (Bala et al., 2010; Cao et al., 2011). When models are forced by an instantaneous increase in CO_2, they show an instantaneous decrease in precipitation (caused by either or both of the "direct" or the "disequilibrium" terms), after which precipitation then rises linearly with temperature as the climate slowly warms. By contrast, when the same models are forced by an equivalent abrupt change in solar radiation they show little immediate effect. We reproduce this phenomenon for the CCSM3 model in Fig. 1 (see Supplement Sect. A for descriptions of model runs). The offset in global mean precipitation between the solar- and CO_2-forced cases is difficult to explain in a purely disequilibrium framework and seems to require some direct effect.

The offset is also difficult to explain in a purely fast/slow framework, however, since it would require that CO_2 forcing produces a direct negative effect on precipitation while solar forcing has no direct effect (e.g. Cao et al., 2011). In a simple surface energy-budget perspective, solar-forced runs *should* show a positive direct effect, since increased shortwave radiation from the sun increases surface energy available to drive evaporation. Bala et al. (2008) follow this line of thought and argue that the increased equilibrium precipitation per warming in solar-forced vs. CO_2-forced climates is due to increased net radiative flux at the surface available in the solar-forced case and not to a reduction in precipitation in the CO_2-case. The solar/CO_2 differences could be explained by a combination of both effects: by assuming that all climates, regardless of forcing agent, show a disequilibrium suppression of precipitation, and that in the solar case this response is nearly cancelled, at least in the global average, by a radiatively-driven precipitation enhancement. In the absence of a definitive test that

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can discriminate between these scenarios, however, the relative importance of the different mechanisms remains an open question.

2 Methodology

We propose here a series of tests that can help clarify the mechanisms driving transient precipitation effects. All tests rely on the regional manifestation of transient precipitation effects rather than on the global aggregates shown in Fig. 1. The use of spatial information allows us to evaluate the relative importance of ocean heat uptake and climate disequilibrium vs. direct radiative effects by testing:

1. *Whether transient precipitation shows a land/ocean contrast*. If ocean heat uptake is an important driver of transient precipitation effects, then these effects should appear predominantly over the ocean and we should see contrasting behavior between land and ocean.

2. *Which representation produces the greatest independence in coefficients*. Each representation of transient precipitation effects – pure fast/slow (Eq. 4), and pure disequilibrium (Eq. 3) – posits a different set of driving physical phenomena, and arranges terms differently to represent those phenomena. If a representation is physically meaningful, the coefficients of those terms should be independent. These relationships obviously cannot be examined with only a global aggregate, but can be examined with separately-fit regional coefficients at the native model resolution.

3. *Whether the global average difference between solar and CO_2 cases is outweighed by regional variation*. If similar distinct regional patterns in transient precipitation appear in both forcing agents, that are locally much stronger than global mean difference between forcing scenarios, then we would conclude that disequilibrium is important for both.

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Finally, we examine the evolution of surface radiation fluxes in both solar- and CO_2-forced cases to help explain the insights derived from these tests.

We conduct the tests described above using a combination of archived runs and custom-generated general circulation model simulations. For our in-house model studies, we use the widely-studied and open-source Community Climate System Model 3 (CCSM3) (Collins et al., 2006). We apply different forcing changes for different purposes, but the bulk of the studies presented here involve instantaneous increases in forcing from pre-industrial conditions, achieved by changing either solar insolation or CO_2 concentrations. Runs with different forcing agents are paired to match the same initial temperature changes and presumably same final equilibrium temperature (700 ppm CO_2 paired with 2.55 % increase in solar insolation). Equilibrium values are taken from a multi-millennial run with CO_2 stabilized at the same value (700 ppm). All runs use a fully-coupled general circulation model because achieving sufficient signal-to-noise to evaluate regional transient precipitation responses (i.e. ΔP vs. ΔT) requires the slow warming of a model with a realistic ocean. Equilibrium conditions must be evaluated with the same fully-coupled model because a slab-ocean model will not necessarily reproduce the regional patterns of a full GCM (Danabasoglu and Gent, 2009). To obtain the necessary runs, we use the low-resolution version of CCSM3 (Yeager et al., 2006) with T31 spectral resolution for the atmosphere ($\approx 3.75^{\circ} \times 3.75^{\circ}$). This choice allows sufficient regional detail but also permits long runs to near-equilibrium. Model runs are described in more detail in Supplement Sect. A.

3 Land-ocean contrast

Although most previous studies of transient climate effects have involved global aggregates, the transient response should be stronger over the ocean than over land if it is driven by delayed warming at the ocean surface. The presence or absence of land/ocean contrast is therefore diagnostic of the underlying mechanism affecting precipitation. The distinction is also important for predictions of impacts, since human

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welfare and ecosystems are primarily affected by precipitation over land. Because the Earth's surface area is dominated by ocean, globally averaged model results previously reported (e.g. Andrews and Forster, 2010; Cao et al., 2011) could reflect primarily an ocean phenomenon, with a smaller or nonexistent response over land.

Previous studies that considered land and ocean precipitation separately do in fact suggest that their precipitation responses may be different (Mitchell, 1983; Dong et al., 2009; Lambert et al., 2011). Mitchell (1983) found land/ocean contrast in precipitation change in experiments where CO_2 concentrations were increased instantaneously but sea surface temperatures held fixed (though contrast could have resulted from the different treatment of land and ocean). Lambert et al. (2011) presented output from five instantaneous-CO_2-doubling GCM experiments and showed that in all models ocean precipitation momentarily decreased significantly while land precipitation was generally inconclusive. These experiments were however hampered by low signal-to-noise: four used slab-ocean models and the single coupled model run involved only a single realization.

In this study we use both a multi-model comparison of archived data and new CCSM3 experiments and find that transient precipitation effects are indeed dominated by the oceans. First, we extend the analysis of Andrews and Forster (2010), who considered global average output from 13 models in the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset (Meehl et al., 2007). We follow the same approach, but divide model output into land and ocean components (Fig. 2). Following Andrews and Forster (2010), we use archived "1pctto2x" model runs, in which CO_2 rises by 1 % yr^{-1} until it doubles in model year 70, and then remains constant for a further 150 yr. The land-ocean contrast in precipitation response is clearly evident in the multi-model mean. Precipitation over the ocean demonstrates behavior consistent with that found for the global mean in Andrews and Forster (2010), with a break in slope at stabilization. (Ocean only $\Delta P/\Delta T$ increases from 1.7 to 3.0 % K^{-1}, whereas global data showed a change from 1.5 to 2.4 % K^{-1}.) Over land, however, the slope actually decreases from 1.5 to

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$0.8\,\%\,K^{-1}$ after stabilization. Individual models are largely consistent with the model mean, with 12 of 13 models showing increased precipitation response ($\%\,K^{-1}$) after CO_2 stabilization over the ocean, implying a suppression of ocean precipitation during CO_2 rise. Over land, precipitation per warming decreases after stabilization in 11 out of 13 models (one model shows an increase, while the other remains constant to within $0.1\,\%\,K^{-1}$); however, intrinsic variability over land means that signal to noise is low (see Supplement Sect. B).

To definitively confirm the land/ocean distinction, we also drive CCSM3 with a CO_2 trajectory designed to generate strong deviations from equilibrium, improving the chance that any transient effect will rise above the intrinsic natural variability in land precipitation. Specifically, we increase CO_2 gradually from 391 ppm in model year 2010 to 1100 ppm in 2110, and then instantaneously remove CO_2 to bring the atmosphere back to 300 ppm (see Supplement Sect. A). This "air capture" scenario is similar to that of Cao et al. (2011), who showed that abrupt reduction in CO_2 caused a temporary spike in global mean precipitation, even while global mean temperature was dropping. While such a rapid drop is unrealistic, this type of extreme experiment can provide insight into transient climate physics (e.g. Held et al., 2010).

Our study confirms the transient precipitation spike is confined to the ocean (Fig. 3). Over the ocean, precipitation increases sharply as expected immediately after CO_2 drawdown (Fig. 3a), consistent with the globally-averaged results of Wu et al. (2010). Precipitation change ΔP at a given time depends not only on the current ΔT but on the history of the atmospheric CO_2 concentration (Fig. 3c): for a given temperature anomaly, precipitation is larger during the cooling period than during the warming period. Over land, the data is noisier, but the transient effect is definitely smaller, and if present appears to be acting in the opposite direction than over the ocean (Fig. 3b, d).

Finally, the land/ocean contrast is present for all forcing agents. Although global mean precipitation in a solar-forced case appears to show little transient effect (Fig. 1), division into land and ocean reveals that ocean precipitation in the solar-forced case does in fact show an initial decrease, while land precipitation shows an equivalent increase (Fig. 4). Precipitation in the solar-forced case in fact resembles that of the CO_2-forced case, sharing the same land-ocean contrast, only with a constant positive offset. The land/ocean contrast in transient precipitation effects supports the hypothesis that ocean heat uptake is a significant driver of transient precipitation change and is difficult to explain as a direct effect alone. Although these results are not alone conclusive, they are consistent with the hypothesis of a superposition of effects: both forcing cases may experience a transient precipitation effect driven by ocean heat uptake, with the offset provided by a positive direct effect in the case of solar forcing, or at least a net positive difference driven by direct effects. These results also highlight the limitations of using global aggregates for inferring impacts on human societies, since the transient precipitation effect over land acts in the opposite direction from that of the global mean.

4 Regional patterns: correlation of coefficients under CO_2 forcing

The regional pattern of transient precipitation provides information as to which end-member representation of transient precipitation (fast/slow in Eq. 4 or disequilibrium in Eq. 3) is more physically meaningful. If the terms in either representation capture distinct physical phenomena, the regional expressions of those phenomena should be different, and the regional values of the coefficients should therefore be independent. The terms in the unphysical relationship would however be necessarily correlated. We showed in Sect. 1 that the terms of Eq. (2) (taken from Allen and Ingram, 2002), where a is a coefficient for a temperature-dependent term, b a radiative effect, and c a heat uptake effect, could be rearranged to imply either a pure radiative driver of transient precipitation, with fast/slow coefficients being $\alpha = a + c$ and $\beta = b - c$, or a pure ocean-heat uptake driver, with disequilibrium coefficients $c_1 = a + b$ and $c_2 = -b + c$. That is, a representation that assumes a purely direct radiative effect folds a part of any disequilibrium effect into its temperature-dependent term, and a representation that assumes a pure ocean-heat-uptake effect folds any radiative effect into its temperature-dependent term. (The non-temperature-dependent terms in the two representations

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are identical, other than the sign convention, and capture all transient effects.) If the true physical mechanism driving transient precipitation involved only heat uptake ($b = 0$), then erroneous use of the fast/slow representation would yield highly correlated terms, since $\alpha = c_1 + c_2$ while $\beta = -c_2$. Conversely, if the true physical mechanism involved only direct radiative effects ($c = 0$), then erroneous use of the disequilibrium representation would again yield highly correlated terms, since $c_1 = \alpha + \beta$ while $c_2 = -\beta$.

The CO_2-forced model runs we have conducted allow us to extract these coefficients at native model resolution. For the equations described above, coefficients can only be derived using a long model run out to near-equilibrium. In the disequilibrium representation, the coefficients c_1 are the local equilibrium hydrological sensitivities: at each grid-point $c_1 = \Delta P_{eq}/\Delta T_{eq}$. Once the equilibrium temperatures are known, the c_2s can then be derived from an instantaneous-forcing run, either by measuring the instantaneous precipitation suppression – the intercept of ΔP vs. ΔT after a forcing change is $c_2 \Delta T_{eq}$ – or by measuring the recovery from that suppression – the slope of ΔP vs. ΔT once forcing has stabilized is $c_1 + c_2$. In the fast/slow representation described here, that slope is the slow term α, and the the intercept at each model grid-box is the fast term $\beta \Delta T_{eq}$ (Fig. 5).

To follow the convention of the field, we show here not the β above but a modified coefficient β_{CO_2}. Most modeling studies of transient precipitation have not made use of long runs and so cannot extract the β that would make the fast/slow and disequilibrium representations exactly analogous. Instead, they express the fast term as a function not of the locally-variable equilibrium temperature change but of the globally homogeneous radiative forcing that produces that change. In this framework the instantaneous precipitation suppression after an instantaneous rise in CO_2 forcing (the intercept on a plot of ΔP vs. ΔT) is $\beta_{CO_2} \log_2 \{700/CO_{2,PI}\}$, allowing coefficients to be derived from only short model runs (Gregory and Webb, 2008; Cao et al., 2011) or from instantaneous forcing changes performed with sea surface temperatures held fixed (Bala et al., 2010; Andrews et al., 2010). This representation is actually more consistent with the

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physics proposed by Allen and Ingram (2002), that transient effects are governed by global radiative forcing (their transient term is bR) rather than by local equilibrium temperature change. On a regional basis, the coefficients β_{CO_2} and β differ by a scaling of the regional pattern of ΔT_{eq}. Because equilibrium temperature has no strong longitudinal structure, the difference should be of secondary importance to correlations. (For proof, see Supplement Fig. S8a and b.) The slight nonlinearity of ΔP with ΔT that we have observed in very long-term runs also does not significantly impact our analysis (see Supplement Sect. C1 and Fig. S7).

Scatterplots of the regional coefficients for CO_2-forced climate change demonstrate that the terms of the disequilibrium representation are largely independent (Fig. 6a, $r = 0.25$), while those of the fast/slow representation are highly correlated (Fig. 6b, $r = -0.94$). The fast/slow formulation attempts to capture independent components of transient precipitation change – a direct response to the forcing agent and a response to the change in temperature – but it is evident that the terms are not in fact independent. The correlation of the fast/slow terms can be seen by eye in maps of the regional expressions of coefficients (Fig. 7). In the disequilibrium framework, equilibrium hydrological sensitivity c_1 is largely a function of latitude, with precipitation increase in the wet tropics and reduction in the dry subtropics, as expected (Fig. 7a). In contrast, disequilibrium precipitation effects c_2 show a strong longitudinal gradient, with precipitation suppression in the Central and East Pacific and enhancement in the Indian Ocean/warm pool region (Fig. 7b). In the fast/slow framework, transient precipitation effects are nearly identical to the CO_2-forced case, as expected (Fig. 7d), but α now also shows the same longitudinal dependence as the transient response (Fig. 7c). Precipitation changes in this framework would have to be explained as a longitudinally varying fundamental hydrological sensitivity that is partially compensated for by a similarly patterned direct effect of opposite sign. These results imply that in CO_2-forced climates, any direct radiative effect is a less important driver of regional transient precipitation effects than is ocean heat uptake (climate disequilibrium).

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This result is robust across forcing scenarios and appears to be robust across models. For runs of the same model used here (CCSM3) forced with a larger CO_2 change (an instantaneous jump from 289 to 1400 ppm), α and β_{CO_2} show a similar strong correlation (Supplement Fig. S10, $r = -0.91$). We also examine two models that archived "2xco2" runs (instantaneous doubling of CO_2) in the CMIP3 archive (Meehl et al., 2007), namely the UK Met Office Hadley Centre Global Environmental Model version 1 (UKMO_HADGEM1) and the Meteorological Research Institute (Japan) Coupled Global Circulation Model version 2.3.2 (MRI_CGCM2.3.2). Both experiments used GCMs with slab-ocean models (SOMs) that equilibrate in decades, allowing extraction of equilibrium hydrological sensitivities c_1. Though signal-to-noise is worse in fast-equilibrating models, both show similar correlations of coefficients, with greater independence of terms in a disequilibrium framework (Supplement Figs. S11 and S12).

The strong regional variation in coefficients means that global mean values provide an incomplete picture of transient precipitation change. Regional expressions of hydrological sensitivities (c_1 or α) and transient effects (c_2 or β_{CO_2}) are locally much larger in absolute magnitude than their corresponding global values, with changes in sign over large regions (Fig. 7a–d). Global net hydrological sensitivity in our CCSM3 stabilization run ($c_1 = 1.9\,\mathrm{cm\,yr^{-1}\,K^{-1}}$) is dominated by precipitation change in the wet inner tropics, where response is up to $15\,\mathrm{cm\,yr^{-1}\,K^{-1}}$. That change is also large in fractional terms, approaching Clausius-Clapeyron ($\approx 7\,\%\,\mathrm{K^{-1}}$) for the average inner tropics, and exceeding it in many individual locations. (For similar maps expressed in fractional precipitation change $\%\,\mathrm{K^{-1}}$, see Supplement Fig. S9a). Globally, instantaneous transient precipitation suppression is about half as large as the ultimate net equilibrium response ($c_2 = 0.8\,\mathrm{cm\,yr^{-1}\,K^{-1}}$) but locally can be twice the local hydrological sensitivity in magnitude and acting in either direction. (In the fast/slow framework, net precipitation would be represented as the sum of a larger hydrological sensitivity of $\alpha = 2.7\,\mathrm{cm\,yr^{-1}\,K^{-1}}$, with approximately one third of this being permanently offset by a direct effect of the forcing agent). In both frameworks, global transient precipitation suppression is dominated by a relatively small region in the central Pacific.

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5 Regional patterns: similarities between forcing agents

Comparison of the regional expression of transient precipitation effects under different forcing agents further clarifies their governing mechanisms. If global mean ocean heat uptake is the driver of transient precipitation effects in CO_2 forced runs, those effects should appear for other forcing agents as well, since ocean uptake occurs whenever climate is in disequilibrium. The solar-forced runs show little transient precipitation effect in the global average, but we showed in Sect. 3 that solar-forced runs do show precipitation suppression over the ocean after a forcing change, with land/ocean contrast similar to that in CO_2-forced cases (Fig. 4). The regional precipitation patterns of Fig. 7 further support the inference that ocean heat uptake effects are manifested in solar-forced climates as well, and that the net positive precipitation offset between solar- and CO_2-forced climates is due to a separate mechanism.

Although the solar-forced case shows only a small global average transient precipitation effect, its regional transient precipitation responses are large and have a complex spatial pattern very similar to that of CO_2-forced case (Fig. 7f, and compare to Fig. 7d). The fast/slow coefficients α (cm yr^{-1}) and β_S (cm yr^{-1} per percentage increase in solar constant) derived from a solar-forced run are highly correlated, as they are for CO_2-forced runs (Fig. 6c, $r = -0.92$, and see Supplement Fig. S13c for a demonstration that β_S is similar to β_{CO_2}). While some authors have argued that the transient precipitation response is a specific feature of CO_2 forcing alone (Cao et al., 2011), it is evident that transient precipitation in the CO_2 and solar-forced cases share some fundamental physics in common.

Regional precipitation does differ between the CO_2 and solar forced runs, but the difference consists of a more globally homogeneous, universally positive offset. That offset is also much smaller than local transient responses. To facilitate comparison of the sizes of these effects, we show in Fig. 8a–c the equilibrium precipitation for the CO_2-forced run, the instantaneous transient effect for the same run, and the difference between precipitation for solar and CO_2 forced runs averaged for 300 model-years.

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The offset has some spatial structure, with a slight reduction at higher latitudes likely corresponding to reduced solar insolation with latitude, and reduced drying of the subtropics in the solar-forced case. Still, both magnitude and regional variation of the offset are considerably less than those of the component of transient precipitation effect that is shared across forcing agents. That structure of the offset remains nearly constant throughout time (see Supplement Fig. S13), even while the regional pattern of precipitation shifts substantially from the initial transient response (Fig. 8a) to the final pattern of equilibrium hydrological sensitivity (Fig. 8b). The transient response of precipitation in a solar-forced case thus appears to consist of two components: a globally positive increase that manifests immediately and is constant thereafter, and an evolving component with complex regional pattern similar to the response of a CO_2 forced climate. These results suggest that ocean heat uptake drives some part of precipitation behavior in all transient climate scenarios, regardless of the forcing agent.

6 Surface energy budget comparison

Analysis of the surface energy budget is useful for understanding precipitation responses, since all precipitation is derived from evaporation, and any change in global precipitation must necessarily correspond to a change in latent heat flux. The latent heat flux in turn is constrained by the fact that surface energy fluxes must balance. The surface energy budget in transient climates has been previously studied by authors including Wu et al. (2010) and Cao et al. (2011), who arrived at contradictory conclusions, with Wu et al. (2010) concluding that ocean heat uptake played a role in transient precipitation effects and Cao et al. (2011) concluding that "ocean heat uptake cannot explain the specific behavior of the latent heat flux change in response to the CO_2 forcing". As mentioned previously, Bala et al. (2008) studied only equilibrium climates, but concluded that the greater precipitation in solar-forced climates was due to a positive direct effect from solar insolation rather than a negative direct effect due to CO_2.

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We examine here the surface energy flux response to the instantaneous forcing change in our paired CO_2- and solar-forced runs discussed above. Fig. 9 shows the evolution of anomalies in surface energy flux and their residual, which is approximately ocean heat uptake. (The residual is the transport of energy between surface and subsurface and includes heat transfer to ocean or freshwater, to soil, or to melting of ice, but is dominated by ocean heat uptake). First, the model runs confirm that heat uptake is negatively proportional to temperature change and for a given temperature is identical regardless of forcing agent, as would be expected if it scales with climate disequilibrium ($\Delta T_{eq} - \Delta T$). After the initial abrupt change, all components of the surface energy budget show near-linear evolution with temperature as the Earth warms over the 330 yr of these runs. (On longer timescales, linearity breaks down.) The response to temperature change for all components of the energy budget is nearly identical in the CO_2- and solar-forced cases, so that components of the energy budget evolve in parallel in the different cases, differing only by initial offsets. For the surface energy residual (heat uptake), there is no offset, and the residuals evolve identically with temperature.

In both forcing scenarios, the abrupt forcing increase and imposition of an abrupt negative disequilibrium drives immediate ocean heat uptake (initially $\approx 6\,\mathrm{W\,m^{-2}}$ over the ocean, or $> 4\,\mathrm{W\,m^{-2}}$ globally). This heat uptake must be accommodated by reduced energy losses or increased energy inputs, that is, by reduced latent heat flux and/or increased shortwave or longwave radiation. (In these runs, initial changes in sensible heat flux are too small to play a major role.) This energetic adjustment must differ over land and ocean, since as expected, the surface energy residual is largest over the ocean, with only a small effect over land (Fig. 9b–c). In both forcing scenarios, as the Earth slowly warms after the initial forcing shock, the surface energy residual (ocean heat uptake) steadily declines with temperature, with the change approximately balanced by a steady increase in latent heat flux (precipitation). (The remaining terms in the surface energy budget also evolve with temperature, reflecting cloud feedbacks and increased sensible heat transport, but these changes themselves nearly cancel.)

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In the CO_2 forcing case, more than half of the initial heat uptake is accommodated by a reduction in latent heat and therefore precipitation. Short-term radiative increases are too small to compensate for the additional energy lost to heat uptake. Incoming shortwave radiation shows a $\approx 1\,\mathrm{W\,m^{-2}}$ increase over both land and ocean that must result from a decrease in cloud albedo, and net downwelling longwave radiation shows a $\approx 1\,\mathrm{W\,m^{-2}}$ increase over both land and ocean, consistent with expectations for clear-sky radiative transfer (Pierrehumbert, 2010, chap. 6). (Increasing atmospheric opacity in the IR will have little effect on surface radiation over much of the spectrum, but is significant in more IR-transparent "windows"). The combined longwave and shortwave increases therefore compensate for less than half of the global-average heat uptake ($>4\,\mathrm{W\,m^{-2}}$) and the remainder must be accommodated by a reduction in latent heat flux, i.e. by precipitation suppression, exactly the transient effect that is observed. This precipitation suppression is likely in turn the driver of the change in cloud albedo. In summary, energy balance considerations require a transient precipitation response to ocean heat uptake. The results here suggest that for CO_2-forced climates, this disequilibrium effect is twice as large as the direct effect and that the direct effect is of opposite sign than that assumed by Andrews et al. (2010) and Cao et al. (2011), it enhances rather than reduces precipitation.

The surface energy budget also explains why little global precipitation suppression is observed in solar-forced runs. Globally, imposition of an instantaneous change in solar radiation produces little disturbance of other components of surface energy balance in our model run. The increase in shortwave forcing (2.55 % increase on $\approx 160\,\mathrm{W\,m^{-2}}$ reaching the ground yields $4\,\mathrm{W\,m^{-2}}$) is almost exactly what is needed to compensate for the global average ocean heat uptake (a bit over $4\,\mathrm{W\,m^{-2}}$). The fact that increased radiation nearly perfectly matches the global heat uptake it drives is in fact expected. If heat uptake N is proportional to climate disequilibrium, i.e. $N = \lambda(\Delta T_{eq} - \Delta T)$, and feedbacks λ are constant, then the forcing R required to produce that disequilibrium is $R = \lambda \Delta T_{eq}$. Immediately after an instantaneous change, when $\Delta T = 0$, the initial heat uptake must necessarily balance the radiative forcing imposed: $N = R$. Barring some

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large direct effect on cloud radiative properties, increasing solar forcing cannot produce a transient suppression of precipitation in the global average.

The energy budget bears out the land/ocean contrast in transient precipitation demonstrated in Sect. 3 for both CO_2- and solar-forced runs. In both cases, reduction in latent heat flux and precipitation suppression is manifested only over the ocean, where the ocean heat uptake occurs (Fig. 9b). In both cases, radiation increases of $\approx 2\,\mathrm{W\,m^{-2}}$ from longwave and shortwave fluxes in the CO_2-forced case and $4\,\mathrm{W\,m^{-2}}$ additional shortwave insolation in the solar-forced case are insufficient to match the $6\,\mathrm{W\,m^{-2}}$ local heat uptake. The imbalance must be compensated by a reduction of latent heat flux and precipitation suppression. Over land, where heat uptake is minimal, the increased radiative fluxes in both cases provide a net *increase* in energy for evaporation, mandating an increase in latent heat flux and so precipitation enhancement (Fig. 9c). These energy budget considerations therefore explain the presence of land/ocean contrast in transient precipitation response cases seen in Fig. 4, as well as why the contrast is similar in magnitude for both forcing agents.

7 Conclusions

The surface energy budget study of Sect. 6 shows that the transient precipitation effects of the different forcing agents are natural and necessary consequences of energetic constraints and of the dependence of ocean heat uptake on climate disequilibrium. A CO_2-forced case must necessarily exhibit transient precipitation suppression in the global average, and a solar-forced case must to zeroth order show no transient precipitation effects in the global average. The globally averaged consequences of these constraints have been observed by many other researchers (Cao et al., 2011; Andrews et al., 2010; Bala et al., 2010) but the globally averaged picture has contributed to some confusion over the physical mechanisms driving these changes.

The globally averaged precipitation behavior in transient climates has been well-fit by previous authors using a fast/slow framework that posits no relationship between

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transient precipitation effects and ocean heat uptake. The fit is not informative about physical mechanisms, however, because the framework is degenerate with a disequilibrium framework that posits control only by ocean heat uptake. We show in Sect. 6 that in the model used here (CCSM3), ocean heat uptake is the only component of the energy budget that has transient anomalies in the direction that could drive the observed initial precipitation suppression observed in experiments that raise CO_2 concentration abruptly. Direct changes in both longwave and shortwave forcing are of the opposite sign, and would tend to enhance rather than reduce precipitation. The surface energy budget therefore implies that all net precipitation suppression in warming climates is a direct consequence of ocean heat uptake. It also implies that suppression would occur over the ocean for all forcing agents, with land effects of the opposite sign. We show in Sect. 3 that this land/ocean contrast is manifested in the overwhelming majority of models in the CMIP3 archive, suggesting that these conclusions are robust across models.

The means by which energetic constraints are translated into physical consequences that affect precipitation become more clear on inspection of the regional expression of precipitation evolution. We study that regional expression by deriving coefficients for pure the fast/slow and disequilibrium frameworks at native model resolution, using a combination of model runs that capture responses immediately after a forcing change (for both solar and CO_2 forcing) and very long-term climate equilibrium (for the CO_2-forced case) (see Sects. 4 and 5). For both solar- and CO_2-forced runs, the coefficients of the disequilibrium framework show more independence than those of the fast/slow framework, implying that ocean heat uptake is the largest contributor to regional transient precipitation effects. Solar-forced climates exhibit the same complex pattern of transient precipitation as CO_2-forced climates, including regions of both suppression and enhancement, but in the solar case, this pattern is overlain with a relatively homogeneous positive offset. This overall enhancement of precipitation in solar-forced cases almost exactly counteracts the net global ocean-heat-uptake driven suppression, leaving a very small global average effect. The apparent lack of a transient precipitation

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effect in the solar case is therefore deceptive. The results here suggest that energy balance in solar-forced climates is achieved not by the absence of any transient effect but by the superposition of two physically quite distinct processes.

The physical explanation suggested by the studies here – that ocean heat uptake produces similar effects on precipitation in both solar- and CO_2-forced climates, and that in the solar-forced case, additional net input of shortwave radiation drives an additional precipitation increase – reconciles seemingly contradictory arguments in the literature. The contention by Wu et al. (2010) that ocean heat uptake is important for transient precipitation, and that of Cao et al. (2011) that direct radiative effects have a role in creating the difference between solar- and CO_2-forced runs, appear both correct, but each comprises only a partial explanation for transient precipitation effects. A full explanation requires combining both perspectives. Our results show the complexity of transient precipitation, with strong spatial variability and differing mechanisms operating with different timescales. They also show, however, that the drivers of transient precipitation effects are understandable and consistent with simple physics.

Supplementary material related to this article is available online at: http://www.atmos-chem-phys-discuss.net/12/19649/2012/ acpd-12-19649-2012-supplement.pdf.

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by the various modeling groups, by the Program for Climate Model Diagnosis and Intercomparison, and by the WCRP's Working Group on Coupled Modelling (DOE Office of Science).

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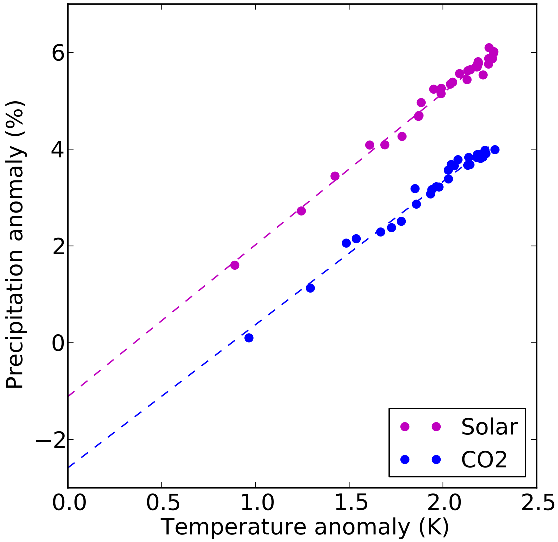

Fig. 1. Global mean temperature and precipitation anomalies from CCSM3 runs with instantaneous rises is CO_2 and solar forcing. Precipitation appears to evolve with temperature with the same slope for both forcing agents and presumably reach different equilibria. This behavior is difficult to explain in a purely disequilibrium framework.

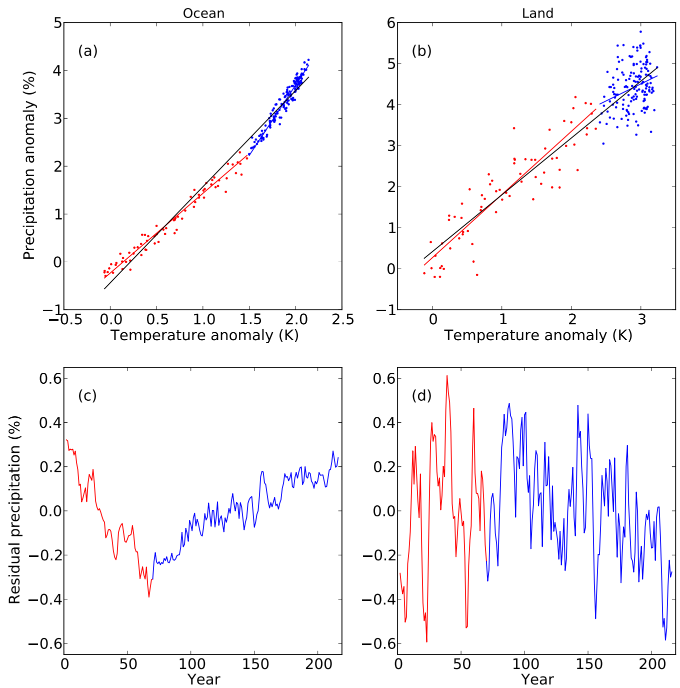

Fig. 2. Multi-model mean temperature anomaly (K) versus precipitation anomaly (%) over **(a)** ocean and **(b)** land for the CMIP3 "1pctto2x" experiment. Red and blue lines correspond to the pre- and post-stabilization segments of a two phase linear fit, while the black line is the single phase linear fit. Panels **(c)** and **(d)** show corresponding residuals for the single-phase fit (with a 5-yr boxcar smoothing applied). For the ocean model output, the two-phase fit is more accurate and the residuals show a clear "V" shape around the stabilization point, suggesting that the precipitation response changes after stabilization. For output over land, the two-phase linear model does not substantially improve the model fit. If present, the "V" shape in the residuals would be inverted.

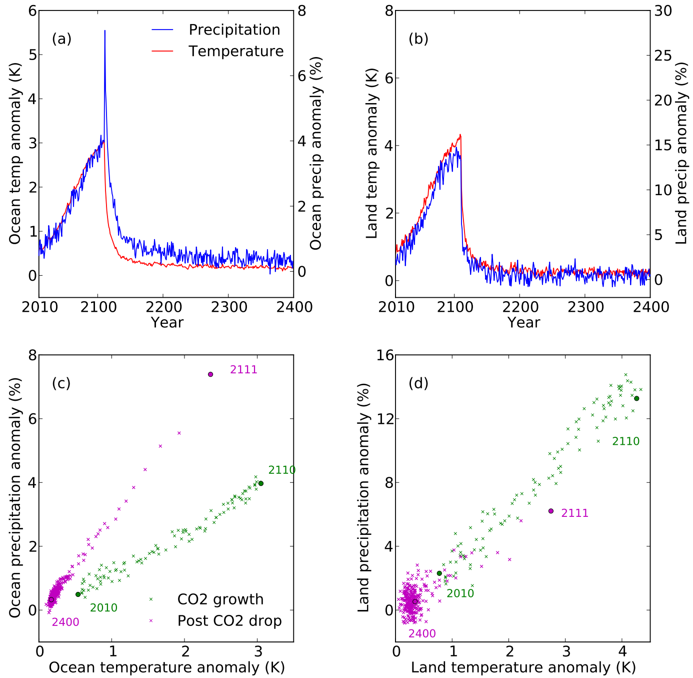

Fig. 3. Global mean **(a)** ocean and **(b)** land temperature and precipitation anomalies for an air capture scenario in which CO_2 rises rapidly from 391 ppm in model year 2010 to 1100 ppm in model year 2110, then drops instantaneously to 300 ppm and remains at that level for ~300 yr (until model year 2400). Results here are the average of five simulations (realizations) of the scenario with different initial conditions. While ocean precipitation spikes immediately following the drop in CO_2, land precipitation follow land temperature more closely. Over the ocean, **(c)** shows that precipitation for a given temperature is clearly larger following the drop in CO_2 than during the ramp-up period. In contrast, **(d)** shows that over land this effect is smaller, and appears to acting in the opposite direction.

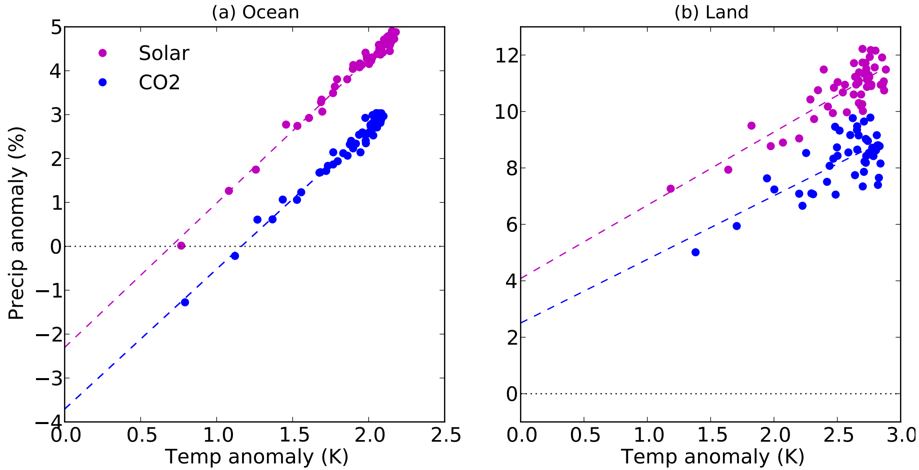

Fig. 4. Global mean ocean and land temperature and precipitation anomalies from CCSM3 runs with instantaneous rises in CO_2 and solar forcing (see Fig. 1 for global average). Land-ocean contrast appears for both forcing agents, nearly identical in magnitude.

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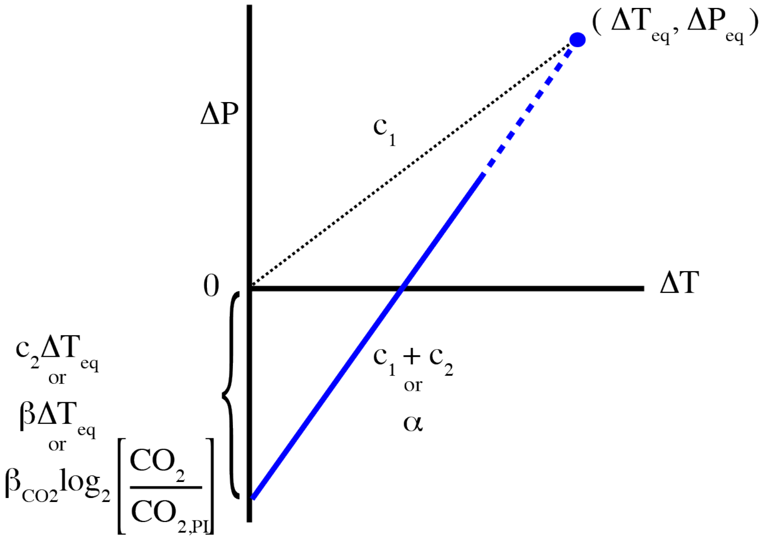

Fig. 5. Cartoon displaying the assumed relationship between temperature and precipitation anomalies for both the disequilibrium and fast/slow frameworks for scenarios where forcing is abruptly changed. Annotations show the means of deriving coefficients used in this work.

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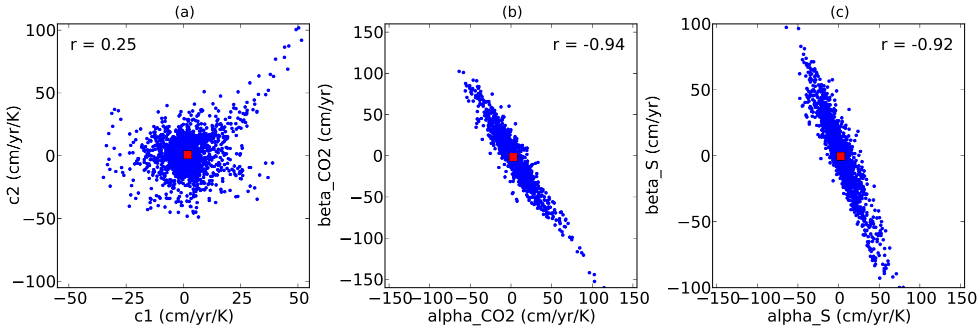

Fig. 6. Scatter plots showing the correlation between regional transient precipitation coefficients in the fast/slow and disequilibrium frameworks (for maps, see Fig. 7). Each blue dot corresponds to a model grid point, while the red square corresponds to global mean values. **(a)** c_1 and c_2, **(b)** α_{CO_2} and β_{CO_2}, and **(c)** α_S and β_S . The r-values are Pearson's correlation coefficients. Disequilibrium coefficients show low correction for the CO_2-forced case, whereas fast/slow coefficients are highly correlated for both forcing agents. (No disequilibrium coefficients could be extracted from the solar-forced runs used in this work.)

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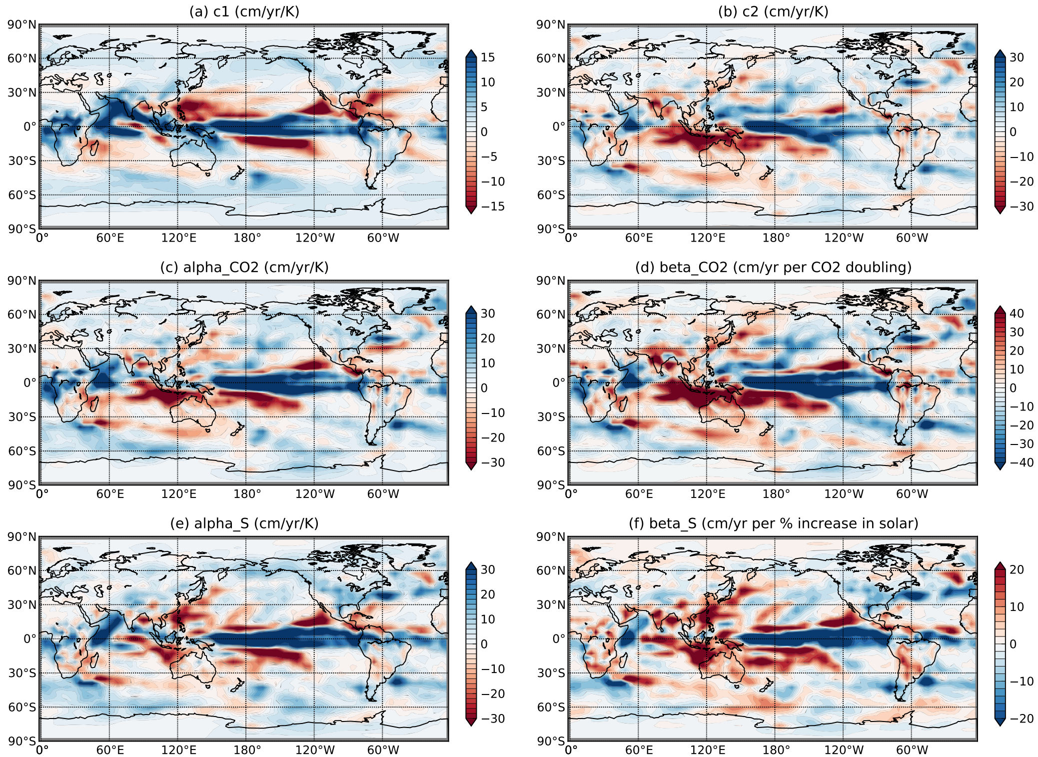

Fig. 7. Regional patterns of the transient precipitation coefficients **(a)** c_1 and **(b)** c_2, **(c)** α and **(d)** β_{CO_2}, and **(e)** α and **(f)** β_S. Coefficients are approximated using data from the instantaneous CO_2 and solar experiments and the multi-millennial CO_2 stabilization experiment. For the CO_2-forced runs, c_1 and c_2 show different longitudinal structure, with equilibrium hydrological sensitivities c_1 a function largely of latitude, while transient effects c_2 show longitudinal asymmetry. α and β_{CO_2} or β_S appear more similar.

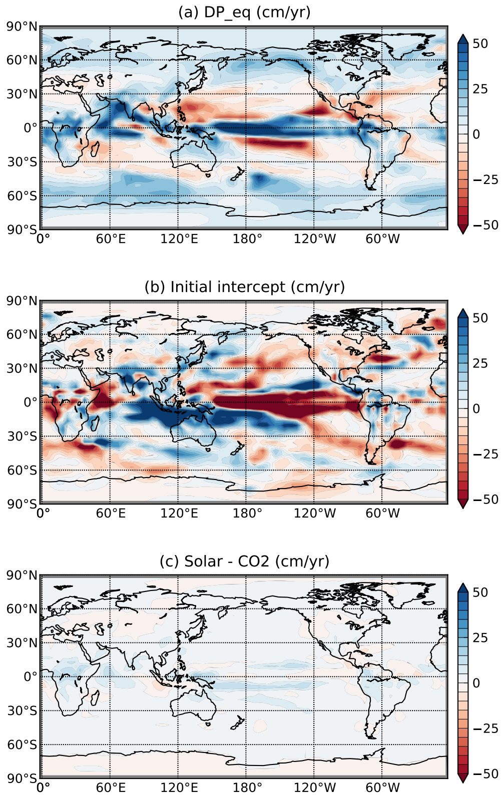

Fig. 8. Comparison of magnitude of precipitation effects: **(a)** equilibrium precipitation change for the multi-millennial CO_2 forced run, **(b)** initial transient precipitation suppression for the instantaneous run with the same CO_2 concentration (derived from the intercept of ΔP vs. ΔT), and **(c)** the difference between paired solar and CO_2 forced runs (averaged over 300 yr). The offset between precipitation in CO_2- and solar-forced runs is small relative to other effects and more globally homogeneous.

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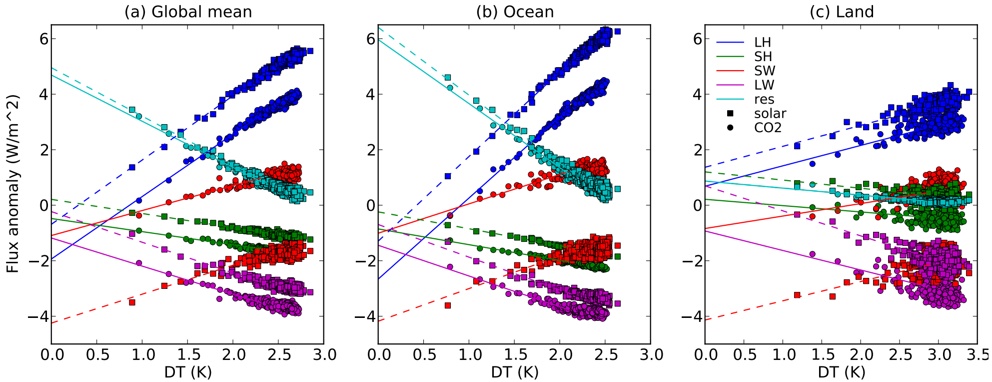

Fig. 9. Energy fluxes into the surface taken from the CO_2- and solar-forced runs for **(a)** global mean, **(b)** ocean only, and **(c)** land only data. Annual averages are marked by squares for solar and circles for CO_2. The linear regression over the first 50 yr is represented by solid lines for CO_2 and dashed lines for solar. Here LH = latent heat flux, SH = sensible heat flux, SW = net shortwave flux, LW = net longwave flux, and rem = remainder, which represents transfer of heat between surface and subsurface, largely via ocean heat uptake.

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