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Concurrent climate impacts of tropical South America land-cover change

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Abstract

The climatic effects of concurrent land-cover changes in Amazonia and Northeast Brazil (NEB) were evaluated by simulations using the Center for Weather Forecasting and Climate Studies Atmospheric General Circulation Model (CPTEC-AGCM). Three experiments were performed: Amazon savannization, NEB desertification and both land-cover changes occurring concurrently. We found that land-cover change from adjacent areas do affect both Amazon and NEB regions and that the negative precipitation anomaly in NEB due to concurrent land-cover changes in Amazon and NEB is weaker than the linear addition of the anomalies considering the land-cover changes separately (synergistic behaviour). A simple mechanism was proposed to explain this behaviour. Copyright © 2011 Royal Meteorological Society

Supporting information may be found in the online version of this article.

Keywords: land-cover change; Amazonia; Northeast Brazil; biomes; AGCM simulation

1. Introduction

In the past three centuries, the replacement of natural ecosystems by croplands has been very significant. Particularly, two regions in tropical South America have been undergoing remarkable land-cover changes: Amazonia (AMZ), where current deforestation rates are close to 12 000 km^2 per year (2007–2008 mean value; http://www.obt.inpe.br/prodes), and Northeast Brazil (NEB), where environmental degradation processes have already affected large portions of the dry shrubland natural vegetation, also known as *caatinga* (Ministerio do Meio Ambiente, 2007, p. 27). According to future scenarios for 2050, about 40% of AMZ area would be deforested (Soares-Filho *et al*., 2006) and more than half of NEB area would be highly degraded (Gonçalves, 2007, see the Supplementary material for an overview of the main goals of this study).

Climate sensitivity to land-cover changes in AMZ and NEB has been evaluated by many studies. For AMZ, climatic impacts due to forest *savannization* (SAV; e.g. Dickinson and Henderson-Sellers, 1988; Nobre *et al*., 1991; Henderson-Sellers *et al*., 1993) or large-scale change from tropical forest to pasture (e.g. Costa *et al*., 2007; Sampaio *et al*., 2007) have been assessed; for NEB, replacement of *caatinga* by semi-desert (Dirmeyer and Shukla, 1996) or desert (Oyama and Nobre, 2004) has also been evaluated. For both regions, the majority of studies found a hydrological cycle weakening, i.e. precipitation, evapotranspiration and moisture convergence decrease in response to land-cover changes.

However, an aspect not considered by the aforementioned studies is that land-cover changes in AMZ and NEB have been occurring (and are expected to keep on occurring) *concurrently*. Climatic impacts due to land-cover changes in a region may teleconnect to other parts of the world (Werth and Avissar, 2002). Therefore, the climatic impacts over AMZ, for example, could be caused not only by local land-cover changes such as deforestation (local effect) but also by the effects of land-cover changes from other regions (nonlocal effect), such as from NEB desertification ((DES) Oyama and Nobre, 2004, p. 3207).

One of the simplest procedures to assess the total or net climatic impact consists of linearly adding the local to all nonlocal effects (e.g. Stein and Alpert, 1993). This is analogous to linearly adding the effects of individual forcings to evaluate the net effect. For instance, Gillett *et al*. (2004) found that the combined climate effects due to different radiative forcings could be linearly added as both greenhouse gases, and the direct effect of sulfate aerosols are known to directly change the surface albedo and therefore the mean annual surface temperature. However, linear addition may not represent the net climatic effects completely; in this case, another term, which we call hereafter the synergy term, would be necessary to include the impacts of nonlinear interactions.

Let $\Delta_{I,J}$ be the climatic effect on a region J, $J =$ AMZ, NEB, due to land-cover change(s) represented by I. The index I may refer to Amazon SAV, NEB DES, the linear sum of individual land-cover changes (SAV + DES) or the combined climatic effects (SD).

The total or net climatic impact of concurrent land-cover changes (SD) may be written as follows:

$$\Delta_{SD,J} = \Delta_{SAV,J} + \Delta_{DES,J} + S_J = \Delta_{SAV+DES,J} + S_J, \quad (1)$$

where S is the synergy term. If the linear addition of local and nonlocal anomalies ($\Delta_{SAV+DES}$) is not close to the combined climate effects (Δ_{SD}), then synergy features related to nonlinear interactions play an important role (Hoffmann and Jackson, 2000). If, on the other hand, $S \sim 0$ (negligible), then the *linearity assumption* holds, i.e. the net effect could simply be computed by $\Delta_{SD} = \Delta_{SAV+DES} = \Delta_{SAV} + \Delta_{DES}$.

The linearity assumption is a key hypothesis to simplify the evaluation of climatic impacts. If it holds, then the net effect of concurrent land-cover changes in AMZ and NEB could be evaluated from previous studies straightforwardly. Moreover, the assumption could be extended to include the effects of land-cover changes from other regions (e.g. replacement of savannas by grasslands/croplands in central Brazil; Hoffmann and Jackson, 2000). Here, we present a new set of simulations using an AGCM to address the validity of the linearity assumption for the climatic impacts of concurrent land-cover changes in AMZ and NEB. This article is organized as follows. In Section 2, the AGCM and the simulations design are described. In Section 3, the results for local, nonlocal and synergy terms in AMZ and NEB are shown. Final considerations are presented in Section 4.

2. Model and simulations

The Center for Weather Forecasting and Climate Studies (CPTEC) AGCM at T126L28 resolution (T126 model; grid spacing of ~100 km and 28 levels in sigma vertical coordinate) is used. This version has higher horizontal spatial resolution than the T062L28 resolution version (T062 model; grid spacing of ~200 km and 28 levels), which was used by several previous climate sensitivity studies (e.g. Oyama and Nobre, 2004; Sampaio *et al*., 2007). The higher resolution of the T126 model allows for better resolving the atmospheric circulation and physics over smaller areas such as NEB.

Three other improvements are included in the T126 model. First, a new shortwave radiation scheme, the CLIRAD-SW-M (Tarasova and Fomim, 2000), is used. Second, the natural vegetation map proposed by Lapola *et al*. (2008) (hereafter LONS08) is used as the land-cover map for the control (CTL) experiment. LONS08 map provides a more realistic natural vegetation distribution over South America. Third, the biophysical parameters for the tropical savannas over central Brazil are updated (Sampaio, 2008, see the Supplementary material for an overview of the main goals of this study).

In this work, land-use-induced land-cover changes (LULCC) are represented by replacement of natural biomes rather than cropland or pastureland replacement. It is a reasonable procedure, because the replacement by savanna or pastureland in AMZ would lead to similar climatic impacts (Rocha, 2001), and extreme land degradation in NEB may be regarded as the replacement of *caatinga* by desert (bare soil). Therefore, for the sake of simplicity, only *natural biomes* are considered.

Four numerical experiments are carried out. In the CTL experiment, undisturbed natural vegetation according to LONS08 map covers all tropical South America (Figure 1(a)). In the SAV experiment, tropical forest in AMZ is replaced by savanna (Figure 1(b)). In the DES experiment, *caatinga* is replaced by desert (Figure 1(c)). The SD experiment refers to concurrent land-cover changes in AMZ and NEB (Figure 1(d)).

Each numerical experiment group is composed of five members. Each member has a 6-year (72 months) numerical integration from June 2002. National Centers for Environmental Prediction (NCEP) analyses from consecutive days are used as initial condition to produce the different ensemble members (lagged average forecasting; Hoffman and Kalnay, 1983). The first 12 months of each integration are neglected due to soil moisture spin up (Oyama *et al*., 2000). Climatological sea surface temperature fields from NCEP Climate Prediction Center (Reynolds and Smith, 1994) are used. For each experiment, the five-member ensemble average is computed to filter out intermember variability.

No validation studies are found for the T126 model. A preliminary comparison between the observed (from the Global Precipitation Climatology Project; Xie *et al*., 2003) and simulated precipitation by T126 and T062 models was carried out (not shown). It was found that the model change from T062 to T126 led to slight improvements in precipitation representation over tropical South America but was not able to change the systematic error pattern (precipitation underestimation over AMZ and overestimation over NEB). Therefore, the assessment of climatic impacts in this work is based on anomaly values, and their degree of uncertainty (which is related to systematic error magnitude) are the same as previous assessments of climatic impacts that used the T062 model (e.g. Oyama and Nobre, 2004; Sampaio *et al*., 2007).

3. Results and discussion

3.1. Local and nonlocal climatic effects

SAV experiment leads to a large area of negative precipitation anomalies from northern AMZ to western parts of NEB on both annual (Figure 2(a)) and seasonal timescales (Supporting information, Figure S1). These results ratify previous studies by Rocha (2001) and Sampaio *et al*. (2007), which have been conducted using the CPTEC AGCM. Positive compensating anomalies are found over western AMZ. The

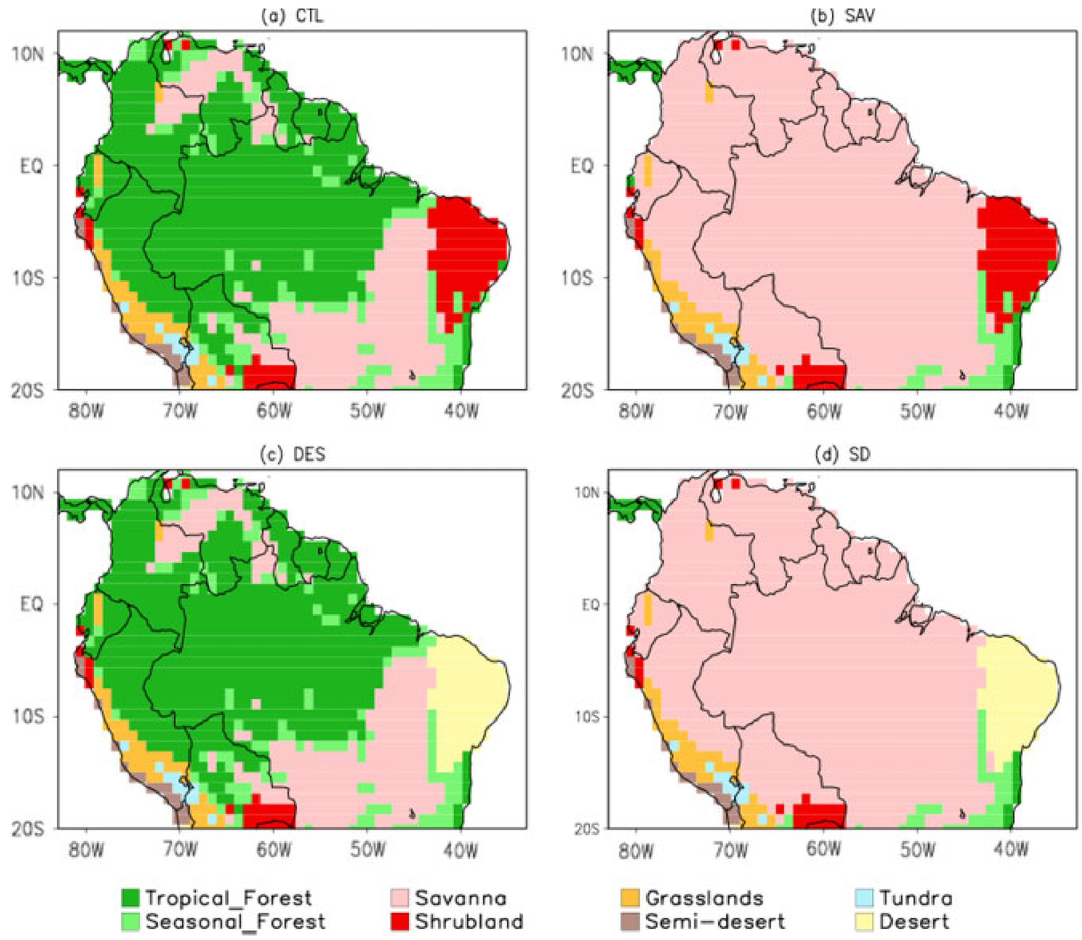

Figure 1. (a) LONS08 natural vegetation map for tropical South America (90 °W – 30 °W, 20 °S – 15 °N) adopted for the CTL run, (b) Amazon SAV, (c) NEB DES and (d) concurrent SAV and DES (SD).

regions of negative and positive precipitation anomalies are related to the downward and upward motion branches, respectively, of the zonal anomalous cell pattern described by Sampaio (2008). This anomalous pattern cell has not been previously found and described by other results of LULCC numerical simulations in AMZ using different AGCMs with lower spatial resolution (Dickinson and Henderson-Sellers, 1988; Nobre *et al*., 1991; Sud *et al*., 1996; Costa and Pires, 2010; among others). Although the negative anomaly signal of precipitation obtained by large-scale model studies is not strictly consistent with results obtained by mesoscale numerical integrations (D'Almeida *et al*., 2007), forest replacement in AMZ is predicted to decrease precipitation over central portions of the basin even when taking into account mesoscale processes such as squall lines and vegetation heterogeneity (e.g. Ramos da Silva *et al*., 2008).

NEB DES (experiment) strongly reduces precipitation in western NEB (WNEB) in annual mean (Figure 2(b)), in agreement with Oyama and Nobre (2004). However, precipitation anomalies are not confined to WNEB, but exhibit a wave-like propagation from WNEB through central to northwestern AMZ, as shown by Souza (2006). Even without a locally persistent negative precipitation anomaly throughout the year, there are significant impacts of NEB DES on AMZ, particularly during insert seasons (Supporting information, Figure S2).

Therefore, SAV and DES experiments ratify the climatic impacts found in previous studies using CPTEC AGCM and also suggest that individual land-cover changes do affect neighbouring areas, i.e. the nonlocal terms $\Delta_{SAV,NEB}$ and $\Delta_{DES,AMZ}$ are not null. To quantify local and nonlocal climatic effects, we define two box-shaped areas according to the maximum negative anomalies of annual precipitation obtained from SAV and DES simulation experiments: AMZ-BOX over eastern AMZ (Figure 2(a)) and NEB-BOX over WNEB (Figure 2(b)). Here, we do not consider AMZ-BOX also covering western AMZ because, as mentioned above, the positive anomalies found by the CPTEC AGCM could not be robust when compared with other model results, which have found negative rather than positive impacts over western portions of the basin and point out the central-eastern areas as the most sensitive to deforestation activities and/or cropland expansion (e.g. Dickinson and Henderson-Sellers, 1988; Nobre *et al*., 1991; Sud *et al*., 1996; Ramos da Silva *et al*., 2008; Costa and Pires, 2010; among others).

According to anomalies of precipitation (ΔP) and vertical motion ($\Delta\omega$; Table I), AMZ-BOX region is clearly influenced by DES simulation on both annual

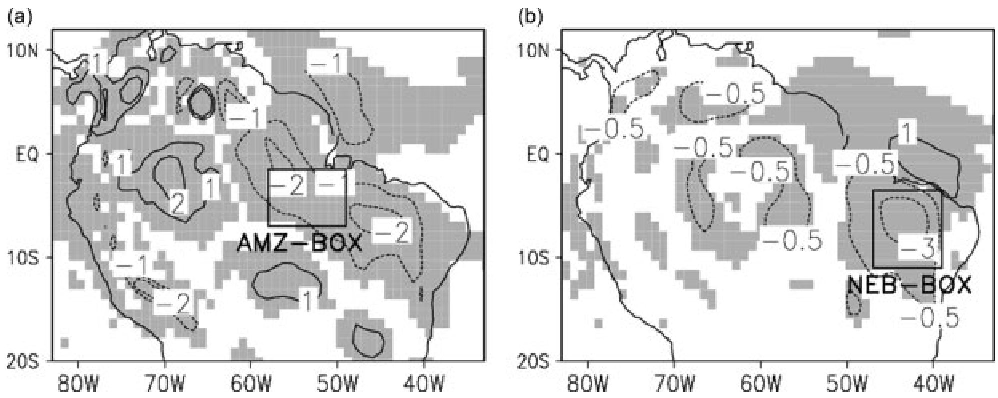

Figure 2. Annual precipitation anomalies (mm day^{-1}) for (a) SAV and (b) DES experiments. Statistical significance using Student's *t*-test is shown by the dark shading referring to 95% confidence interval; dotted and continuous lines represent, respectively, negative and positive anomalies. Box-shaped areas are also depicted within (a) AMZ (AMZ-BOX) and (b) NEB (NEB-BOX).

Table I. Contribution of precipitation (*P*) and vertical motion (ω at 500 hPa) anomalies for AMZ-BOX and NEB-BOX regions for all simulations.[a].

Variable	Timescale	SAV	DES	SAV + DES	SD	DIFF
AMZ-BOX						
	Annual	−1.38	−0.35	−1.73	−1.88	0.15•
	DJF	−0.94	−0.02	−0.96	−1.08	0.12•
ΔP	MAM	−1.53	−0.63	−2.16	−2.49	0.33•
(mm day^{-1})	JJA	−1.86	−0.65	−2.51	−2.40	−0.11•
	SON	−1.21	−0.08	−1.29	−1.54	0.25•
	Annual	−1.38	−0.35	−1.73	−1.88	0.10•
	DJF	−0.94	−0.02	−0.96	−1.08	0.21•
$\Delta\omega$	MAM	−1.53	−0.63	−2.16	−2.49	0.17•
(10^{-5} cb s^{-1})	JJA	−1.86	−0.65	−2.51	−2.40	−0.21•
	SON	−1.21	−0.08	−1.29	−1.54	0.28•
NEB-BOX						
	Annual	−1.30	−2.61	−3.91	−3.11	−0.80*
	DJF	−2.02	−4.02	−6.04	−4.72	−1.32*
ΔP	MAM	−1.15	−3.85	−5.00	−4.65	−0.35•
(mm day^{-1})	JJA	−0.90	−1.50	−2.40	−1.61	−0.79*
	SON	−1.13	−1.05	−2.18	−1.46	−0.72*
	Annual	−0.78	−1.87	−2.65	−2.06	−0.59*
	DJF	−1.32	−3.10	−4.42	−3.37	−1.05*
$\Delta\omega$	MAM	−0.65	−2.64	−3.29	−3.14	−0.15•
(10^{-5} cb s^{-1})	JJA	−0.52	−0.93	−1.45	−0.91	−0.54*
	SON	−0.63	−0.82	−1.45	−0.83	−0.62*

[a] Symbol * (•) indicates the existence (absence) of statistical significance for the difference between SAV + DES and SD (DIFF), calculated from Student's *t*-test of 95% to verify the presence of synergy.

and seasonal timescales, particularly during MAM (rainy season) and JJA (transition from rainy to dry season). Although SAV experiment results in higher local impacts over AMZ, nonlocal effects due to DES experiment account for about 20–30% of the total anomaly in MAM and JJA, when the wave-like propagation of precipitation anomalies from NEB to AMZ is clearer (Supporting information, Figure S1).

NEB-BOX is also clearly affected by SAV simulation on annual and seasonal timescales. Nonlocal effects due to SAV experiment account for about 20–50% of the total anomaly. The influence of SAV simulation on NEB-BOX results from the subsidence branch of the zonal anomaly cell pattern (Supporting information, Figure S2).

3.2. The synergistic climatic effect

3.2.1. Nonsynergy conditions

The validity of the linearity assumption (1) depends on the existence and magnitude of the synergy term. To verify the synergy-term existence, we derive nonsynergy conditions for a key climate variable, precipitation (P), by assuming that the system nonlinearities (which are the source of synergistic behaviour) could be neglected. On monthly timescales, for equatorial areas, the atmospheric thermodynamic energy equation, which drives the convection activity and thus the precipitation amount, could be simplified, at first order, into a simple linearized set of equations, i.e. a balance between the diabatic and adiabatic terms (Wallace and Hobbs, 2006). This balance could be represented by $P = -\alpha\omega$, where α is a parameter related to static stability and ω the omega vertical velocity. Assuming that static stability is constant, i.e. variations of α could also be neglected; anomalies (Δ) of P and ω due to SAV and DES are given by

$$\Delta P_{\mathrm{SAV},\bullet} = -\alpha\,\Delta\omega_{\mathrm{SAV},\bullet}, \quad (2)$$

$$\Delta P_{\mathrm{DES},\bullet} = -\alpha\,\Delta\omega_{\mathrm{DES},\bullet}, \quad (3)$$

$$\Delta P_{\mathrm{SD},\bullet} = -\alpha\,\Delta\omega_{\mathrm{SD},\bullet}, \quad (4)$$

where $\bullet$ = AMZ or NEB. If linearity assumption holds for ω anomalies, then

$$\Delta\omega_{\mathrm{SD},\bullet} = \Delta\omega_{\mathrm{SAV},\bullet} + \Delta\omega_{\mathrm{DES},\bullet}. \quad (5)$$

Adding Equations (2) and (3) and using Equations (4) and (5), it follows that

$$\Delta P_{\mathrm{SD},\bullet} = \Delta P_{\mathrm{SAV+DES},\bullet} = \Delta P_{\mathrm{SAV},\bullet} + \Delta P_{\mathrm{DES},\bullet}, \quad (6)$$

that is, the synergy term ($S_\bullet$ from Equation (1)) could be neglected for P anomalies. Conversely, if $S_\bullet \neq 0$, the synergy term is defined and quantified as the

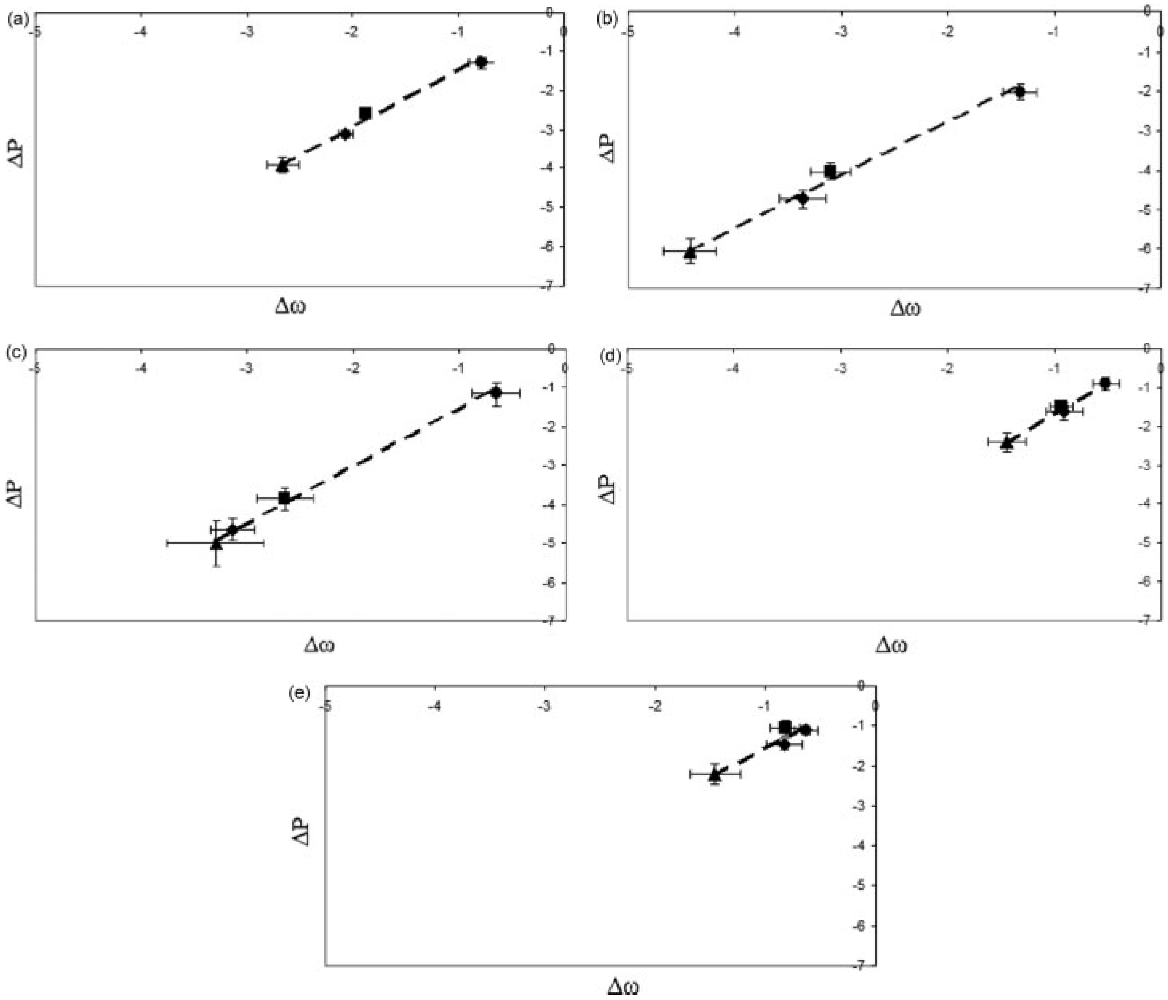

Figure 3. Dependence representation of NEB-BOX's regional mean values of precipitation (mm day^{-1}) and vertical motion (10^{-5} cb s^{-1}) anomalies for (a) annual, (b) December-January-February (DJF), (c) March-April-May (MAM), (d) June-July-August (JJA) and (e) September-October-November (SON) time means. Each symbol corresponds to the contribution of each land-cover change simulation (circle = SAV; square = DES; diamond = SD; triangle = SAV + DES), and the error bars represent the intermember variability.

residual (difference) between the actual values of the system (SAV + DES) and the values of the linearized system (SD):

$$S_{\bullet} = |\Delta P_{\text{SAV+DES},\bullet} - \Delta P_{\text{SD},\bullet}|. \quad (7)$$

Therefore, the two synergy conditions are (1) the linearity between ΔP and $\Delta\omega$ from Equations (2)–(4) and (2) linearity assumption for $\Delta\omega$ (5), which leads to the linearity assumption for ΔP (6).

3.2.2. SD experiment

For AMZ-BOX, P and ω anomalies are linearly related (not shown), the values of $\Delta\omega$ from SAV + DES and SD are close and their differences are not significant (Table I). Thus, the synergy term could be neglected and the linear assumption for precipitation is valid, i.e.:

$$\Delta P_{\text{SD,AMZ}} \sim \Delta P_{\text{SAV+DES,AMZ}} = \Delta P_{\text{SAV,AMZ}} + \Delta P_{\text{DES,AMZ}}.$$

Unlike AMZ-BOX, NEB-BOX has a net precipitation decrease strongly affected by the synergy term; and the difference between SD and SAV + DES is significant (Figure 3 and Table I) except in the MAM (Figure 3(c)). For all other seasons, ΔP and $\Delta\omega$ in SD experiment are less intense than in SAV + DES, i.e. impacts of combined land-cover changes are weaker than the linear sum of effects from individual land-cover changes:

$$|\Delta P_{\text{SD,NEB}}| < |\Delta P_{\text{SAV+DES,NEB}}| = |\Delta P_{\text{SAV,NEB}} + \Delta P_{\text{DES,NEB}}|.$$

This behaviour is more conspicuous during the drier months from June to November (Table I): SD anomalies are close to DES anomalies and the synergy term has a negative value. Although linearity between ΔP and $\Delta\omega$ is found (Figure 3), i.e. assumptions (2–4) hold, whereas assumption (5) of linear addition for $\Delta\omega$ fails; thus, the second nonsynergy condition fails and so does the linear assumption for precipitation.

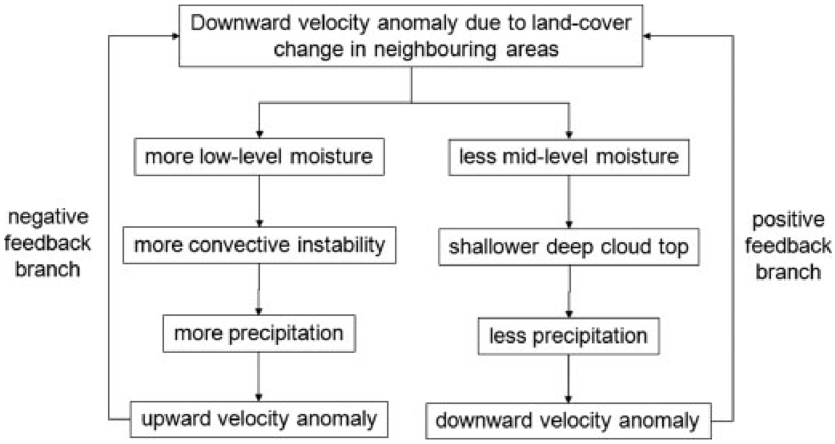

Figure 4. Schematic diagram depicting the negative (positive) feedback branch that may lead to the synergistic (nonsynergistic) behaviour observed by the SD simulation experiment for NEB-BOX (AMZ-BOX) region.

One mechanism that explains the failure of assumption (5) is related to the water vapour profile response to nonlocal vertical velocity anomalies (Figure 4 and Supporting information, Tables SI and SII). Subsidence anomalies (from adjacent areas) tend to simultaneously increase (decrease) low-level (mid-level) moisture content in the atmospheric column over NEB-BOX. More low-level moisture favours convective instability, which increases convective precipitation and the related upward velocity anomaly feeds back negatively into the original anomaly. Conversely, less mid-level moisture favours convective drier air entrainment into updrafts, which decreases convective precipitation and the related downward velocity anomaly feeds back positively into the original anomaly. The net effect would be the balance between the two feedback branches, and the equilibrium anomaly value could be quite different from the original (local) subsidence anomaly depending on the mechanism (hereafter moisture mechanism) strength (Supporting information, Tables SI and SII).

AMZ-BOX is a humid region where moisture is supplied by moist large-scale low-level easterly winds. For NEB-BOX, only in the MAM, moisture supply is high due to the Intertropical Convergence Zone southward displacement. Therefore, for humid regions (AMZ) and/or periods (rainy season of NEB), when moisture supply from large-scale systems is active, the moisture mechanism may be neglected and the linear assumption would hold. During humid periods, this could be explained by the weakening of the vertical moisture gradient due to moistening of mid atmospheric levels (Oliveira and Oyama, 2009), which limits the anomalies of vertical moisture advection and, therefore, the action of the moisture mechanism.

4. Concluding remarks

The climatic effects of concurrent land-cover changes in AMZ and NEB were evaluated by simulations using the CPTEC AGCM. Three experiments were performed: SAV, DES and SD. Besides the local effects of SAV (effects of SAV in AMZ climate) and DES (effects of DES in NEB climate), which have already been studied and were ratified here, we addressed two new aspects over both areas. First, we evaluated the nonlocal effects, i.e. the effects in NEB (AMZ) from the SAV (DES) simulation experiment and second, the synergistic effects of SD simulation over AMZ and NEB.

According to our results, nonlocal impacts are markedly important for both AMZ and NEB regions. Therefore, climate impacts for AMZ and NEB due to land-cover changes may be different from assessments considering only local effects.

In the context of the synergy term, simulation results showed that the net effect of combined land-cover changes in AMZ and NEB (SD) on precipitation could be approximated by a linear addition of the local and nonlocal effects (SAV + DES). However, this linear assumption failed for NEB: the net effect (SD) was weaker than the linear sum between the local and nonlocal effects (SAV + DES). The synergistic mechanism (moisture mechanism) behind this behaviour may be associated to the water vapour profile response to nonlocal vertical velocity anomalies (Supporting information, Tables SI and SII). For humid periods (AMZ and rainy season of NEB) when moisture supply from large-scale systems is active, the moisture mechanism may be neglected and the linear assumption would hold.

For AMZ, the validity of the linearity assumption leads to far reaching consequences. On one hand, if it holds for other ongoing land-use changes (e.g. cropland expansion over Brazilian savanna), a preliminary assessment of the future climate change due to land-cover modification in AMZ could be obtained straightforwardly by adding the precipitation anomalies from individual land-cover change studies. On the other hand, if the validity of the assumption is further extrapolated, then precipitation anomalies related to other processes/forcings (for instance, precipitation anomalies induced by global climate change – e.g. using the results from Salazar *et al*., 2007) could also simply be linearly added. This extrapolation is constrained by the fact that linear addition from different forcings is much more complicated to demonstrate because the number of variables involved would significantly increase. For instance, some future climate scenarios project precipitation decreases for AMZ region. In this case, AMZ basin could not remain sufficiently humid to not be affected by the moisture mechanism described in this work. For NEB, although the linearity assumption is not valid, the linear sum of local and nonlocal effects would be useful to provide an upper bound assessment of the precipitation anomaly, as the synergy term acts to reduce the anomalies' magnitude.

The results obtained here are based on simulations using a particular AGCM. Therefore, to ensure the robustness of our conclusions, simulations with different models (global or regional) are necessary.

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