Chapter 4

Investigating the Relative Roles of the Degradation of Land and Global Warming in Amazonia

Sergio H. Franchito, J. P. R. Fernandez and
David Pareja

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http://dx.doi.org/10.5772/58991

1. Introduction

Large-scale removal of the tropical rain forest will have significant negative effects on regional water and energy balance, climate and global bio-geochemical cycles. Numerical experiments using General Circulation Models (GCMs) [1, 2, 3 and many others], using statistical-dynamical simple climate models (SDMs) [4, 5, 6] and field observations) [7] have shown that the large-scale deforestation in Amazonia may indeed influence regional climate. Reduction in evapotranspiration and precipitation and an increase in the surface temperature in the tropical region occur when the forest is replaced by pasture.

Projections of future climate given in IPCC AR5 (2013) (to be published) indicated that climate change due to anthropogenic human activities is affecting adversely the ecosystems. Many model studies showed that the global warming may affect the biomes distribution over South America, where significant portions of rain forest may be replaced by nonforested areas [8, 9, 10, 11]. These studies suggest that due to increase of greenhouse gases concentration the process of savannization of the tropical forest can be accelerated. This indicates that the future distribution of biomes in the tropical region depends on the combination of the effects of the degradation of land surface and climate changes due to global warming. Some studies have been made to investigate the relative roles of future changes in greenhouse gases compared with future changes in land cover. [12] and [13] compared the climate change simulated under a 2050 SRES B2 greenhouse gases scenario to the one under a 2050 SRES B2 land cover change scenario. It was noted that the relative impact of vegetation change compared to greenhouse gas concentration increase was of the order of 10%, and could reach 30% over limited areas of tropical region. The same methodology was applied for the SRES A2 and B1 scenario over the 2000 to 2100 period [14]. It was also found that although there was no significant effect at the global scale, a large effect at the regional scale may occur, such as a warming of 2°C by 2100 over the Amazon for the A2 land cover change scenario. Recently, studies using SDMs showed that the percentage of the warming due to deforestation relative to the warming when greenhouse gas concentration increase was included together was around 60% in the tropical region [5, 6]. These results suggest that the climate change due to land cover changes may be important relative to the change due to greenhouse gases at the regional level, where intense land cover change occurs. Globally, however, the impact of greenhouse gas concentrations seems to dominate over the impact of land cover change.

Although GCMs and SDMs can provide useful information regarding the response of the global circulation to large-scale forcing, due to their coarse resolution the mesoscale forcing, such as complex topography, vegetation cover, lakes, etc, are not well represented. In this sense Regional Climate Models (RCMs) may be more adequate. RCMs have therefore been developed to downscale larger scale simulations and to provide predictions for specific regions [15, 16, 17, 18].

In this paper the relative roles of the land surface degradation in Amazonia and global warming are investigated using a RCM. The purpose is to inquire how is the effect on the regional climate and aridity due to deforestation and when the increase of concentration of greenhouse gases is also taken into account together. The model to be used is The Abdus Salam International Centre for Theoretical Physics Regional Climate Model v. 4 (ICTP/RegCM4) [19]. In order to take into account the effect of global warming the model will be run using a methodology for generating surrogate climate-change scenarios with a regional climate model [20]. The distribution of aridity is determined using the radiative dryness index of Budyko (AI_B) [21] and the UNEP aridity index (AI_U) [22]. A brief description of the RCM, the methodology employed and the experiments design are given in section 2; the model simulations are presented in section 3 and section 4 contains the summary and conclusions.

2. Regional climate change model

The model ICTP RegCM4 [19] is the version 4 of the regional climate model (RegCM) originally developed at the National Center for Atmospheric Research (NCAR) [15, 16]. The dynamic component of the model is based on the NCAR-Pennsylvania State University meso-escale model (MM5) [23]. For application in climate studies, a number of physical parameterizations were incorporated in the model. More details about the model and physical configurations for South America is given in [19]. In the present study modified parameters of BATS land-surface model for vegetation type 6 (tropical rain forest) are used to reduce the rainfall dry bias over tropical South America, as reported in earlier RegCM versions [24].

The model domain covers the entire South America (Fig. 1), following the CORDEX, an international effort to downscale climate projections over the world using RCMs [25]. The model domain is centered at 22S, 59W, and comprises 202EWx192NS grid points, with a horizontal grid spacing of 50 km over a rotated Mercator projection. Ten-yr simulations were performed (after discarding a 1 yr spin-up period), extending from 1 January of 1990 to 31 December of 1999.

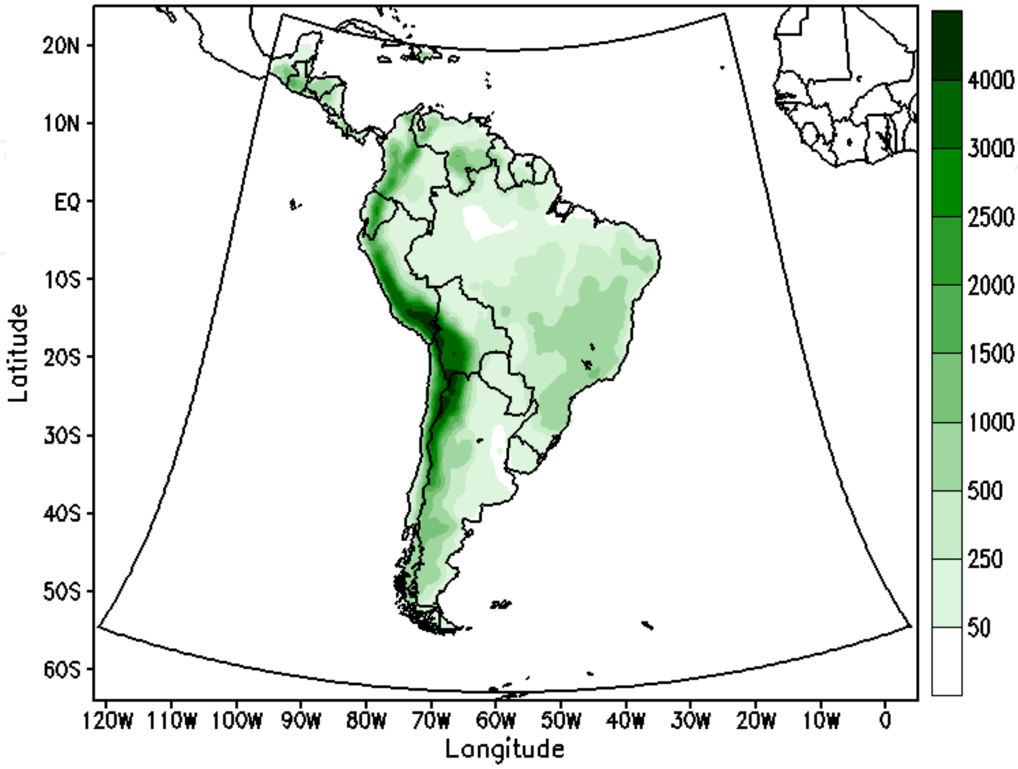

Figure 1. Model domain. Also shown is the topography of South America. Units, m.

2.1. Control experiment model

In the control experiment the model is forced using the ERA-Interim reanalysis data [26]. The greenhouse gas concentration corresponds to the present-day conditions. The distribution of aridity is obtained using the Budyko radiative dryness [21] and the UNEP aridity index [22]. The Budyko index has been used in many studies of land-surface effects, climate change and biogeography [27, 28, 29 and many others]. The UNEP index was adopted by UNEP to produce a dryness map [22].

The Budyko index, AI_B, is defined as AI_B=R/ (LP), where R is the mean annual net radiation; P, the mean annual precipitation and L is the latent heat of evaporation. Thresholds for different climate regimes are defined as:

$0 < AI_B \leq 1$=humid (surplus moisture regime; steppe to forest vegetation)

$1 < AI_B \leq 2$=semi-humid (moderately insufficient moisture; savanna)

$2 < AI_B \leq 3$=semi-arid (insufficient moisture; semi-desert)

$AI_B > 3$=arid (very insufficient moisture; desert)

The UNEP index, AI_U, is defined by AI_U=P / PET, where P is the annual precipitation and PET is the annual potential evapotranspiration. P is provided by the model while PET is calculated using the formula of [30]. Thresholds for different climate regimes are:

$AI_U \geq 1$= humid regime

$0.65 \leq AI_U < 1$=dry land

$0.50 \leq AI_U < 0.65$=dry sub-humid regime

$0.20 \leq AI_U < 0.50$=semi-arid regime

$0.05 \leq AI_U < 0.20$=arid regime

$AI_U < 0.05$=hyper-arid regime

Results of [31] showed that in general the climate variables, such as temperature, precipitation and evaporation, and the distribution of aridity over South America using both the Budyko and UNEP indices, for the present-day climate are well simulated by the model.

2.1.1. Climate change experiment on deforestation

The biomes distribution over South America according to the vegetation types given by BATS1e is given in Fig. 2a. In the deforestation experiment the entire tropical forest zone is converted into short grass (Fig. 2b). So, all the characteristic parameters of the tropical forest are replaced by those from short grass conditions according to BATS1e. Though extreme, it is important to evaluate a scenario of a hypothetical complete Amazon deforestation. The extreme scenario of total deforestation is useful to provide insight into underlying physical principles of the functioning of the climate system. Although it is unlikely that deforestation will affect the entire Amazonian forest, the extreme scenario of total deforestation is useful to identify the sensitivity of the climate system to changes in the land surface properties. In this experiment the effects of deforestation in Amazonia on the regional climate and aridity is studied.

2.1.2. Surrogate climate change experiment including deforestation

In this experiment the effects of global warming is taken into account together with the deforestation in Amazonia. For this purpose the methodology for generating a surrogate climate change scenario with a RCM proposed by [20] is used. It consists of a uniform 3 K temperature increase and an attendant increase of specific humidity. In this scenario, the ERA-Interim dataset of temperature is increased by 3K throughout the atmospheric column and the sea surface temperature OISST dataset [32] are warmed by 3 K. The atmospheric greenhouse gases concentration of the sensitivity experiment is set to two times its present-day values. A global mean equilibrium surface temperature increase of 3 K corresponds approximately to a CO_2 equivalent concentration of 710 ppm [33].

The methodology for generating a surrogate climate change scenario is dynamically consistent and easy to incorporate in a RCM. The procedure can be applied to the study of the regional response to a pseudo-global warming with an accompanying increase of the

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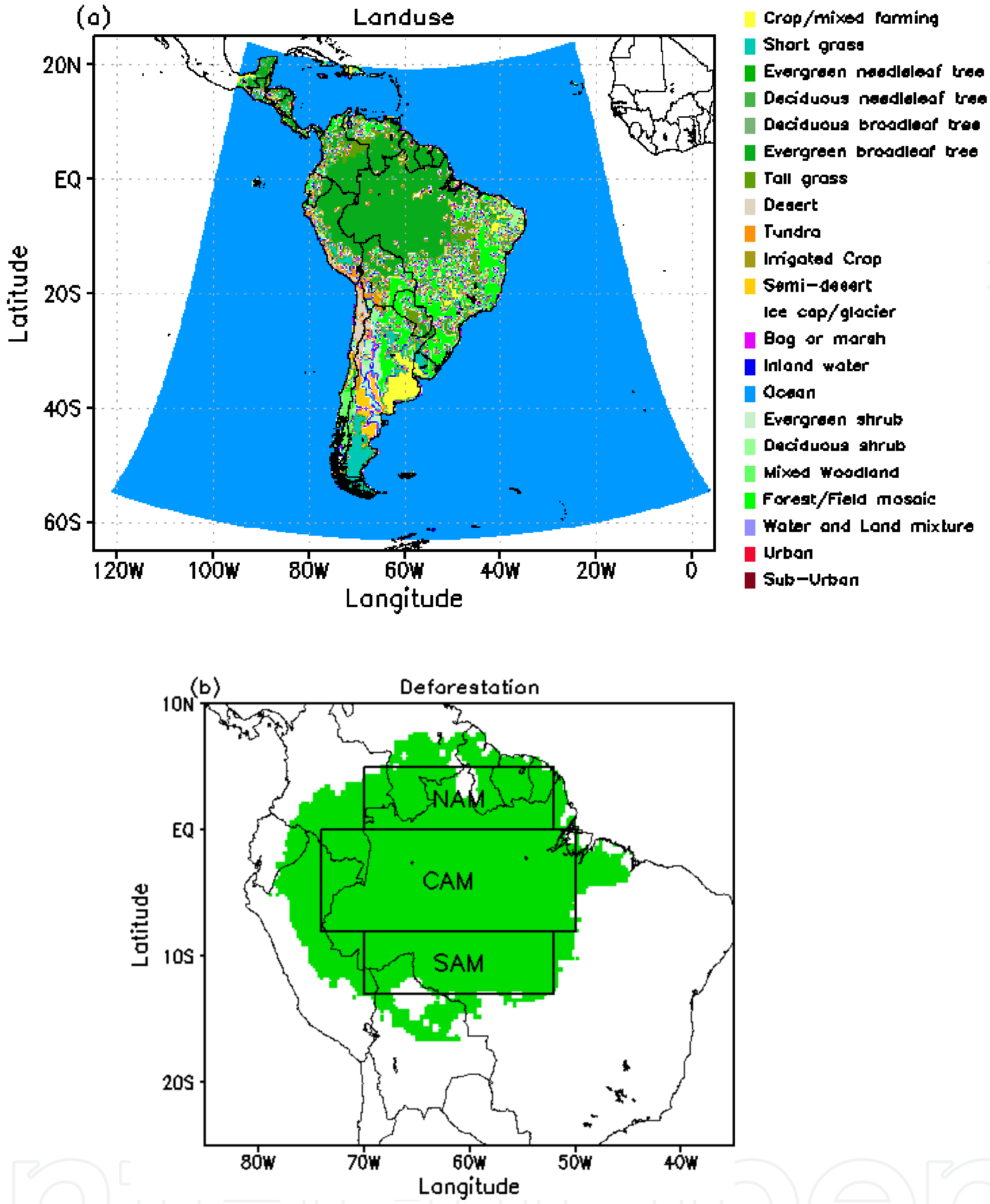

Figure 2. a) Vegetation types over South America according BATS1e; b) Region of Amazonia where the evergreen broadleaf trees are replaced by short grass in the deforestation experiment. Also shown are the areas denoting: north Amazonia (NAM), central Amazonia (CAM) and south Amazonia (SAM).

atmospheric water vapor content. However, the surrogate climate change scenario is only a sensitivity experiment and not a real climate change experiment. In a surrogate climate change scenario the response to a combination of a horizontally uniform thermodynamic modification of the initial and external fields plus an unmodified external flow evolution is studied. Otherwise a real climate change would be accompanied by changes in the planetary and synoptic-scale circulation. In spite of this drawback, the methodology allows us to examine certain processes in isolation [20, 34, 35].

3. Results and discussion

In order to discuss with more regional details the effects of deforestation and the pseudo-warming on Amazonia, three regions are considered: north (0-5N, 70W-52W), central (8S-0, 74W-50W) and south (13S-8S, 70W-52W) Amazonia (Fig. 2b). This is because the changes are different in these regions, as will be seen in the next sections.

3.1. Effect of deforestation

Figure 3 shows the distribution of aridity for the control and deforestation experiments and the change (deforestation minus control) using the Budyko and UNEP indices. As can be seen in Figs. 3a and 3b, areas of humid regime (forest) are replaced by sub-humid regime (savanna) in the part of central Amazonia southward from 5S and in the south Amazonia in the deforestation experiment compared with the control. The Budyko index increases (increase of aridity) in these regions. In the north and most of the central Amazonia the aridity is decreased (Fig. 3c). As shown in Table 1, taking into account the values of AI_B averaged over the entire three regions of Amazonia, the aridity increases 22% relative to the control in the south region. In the north and central areas there is a decrease of the aridity of 4% and 1.1%, respectively. For the case of the UNEP index, it can be noted from Figs. 3d and 3e that dry land substitutes regions of humid regime in Amazonia. The UNEP index decreases (the aridity increases) in the central and south Amazonia while in the north Amazonia it increases, as seen in Fig. 3f. These changes in the UNEP indicate an increase in the aridity of 22% and 4.8% relative to the control in the south and central Amazonia, respectively, while in the north Amazonia there is a decrease of 3% (Table 1).

Although the changes in the distribution of aridity due to deforestation using Budyko and UNEP indices show a very good agreement in the south and north Amazonia, the results diverge in the central region: the use of Budyko index indicates a decrease of aridity while the UNEP index suggests an increase.

Index Budyko	Region	I_B CTRL	I_B defor	AI_B defor minus CTRL	Change in I_B (defor relative to CTRL)	I_B (defor plus pseudo)	I_B (defor plus pseudo) minus CTRL	Change in I_B (defor plus pseudo) relative to CTRL
	North Amazonia	0.74	0.71	-0.03	-4%	0.89	+0.15	+20%
	Central Amazonia	0.92	0.93	-0.01	-1.1%	0.99	+0.07	+7.6%
	South Amazonia	1.00	1.22	+0.22	+22%	0.90	-0.10	-10%

UNEP	I_U CTRL	AI_U Defor	AI_U defor minus CTRL	Change in I_U (defor relative to CTRL)	AI_U (Defor + pseudo)	AI_U (Defor + pseudo) minus CTRL	Change in AI_U (defor + pseudo) relative to CTRL
North Amazonia	2.66	2.74	+0.08	+3%	1.66	-1.00	-37.6%
Central Amazonia	1.68	1.60	-0.08	-4.8%	1.21	-0.47	-28%
South Amazonia	1.36	1.06	-0.30	-22%	1.22	-0.14	-10.3%

Table 1. Values of AI_B and AI_U and the relative changes in the experiments of deforestation and deforestation plus pseudo-warming.

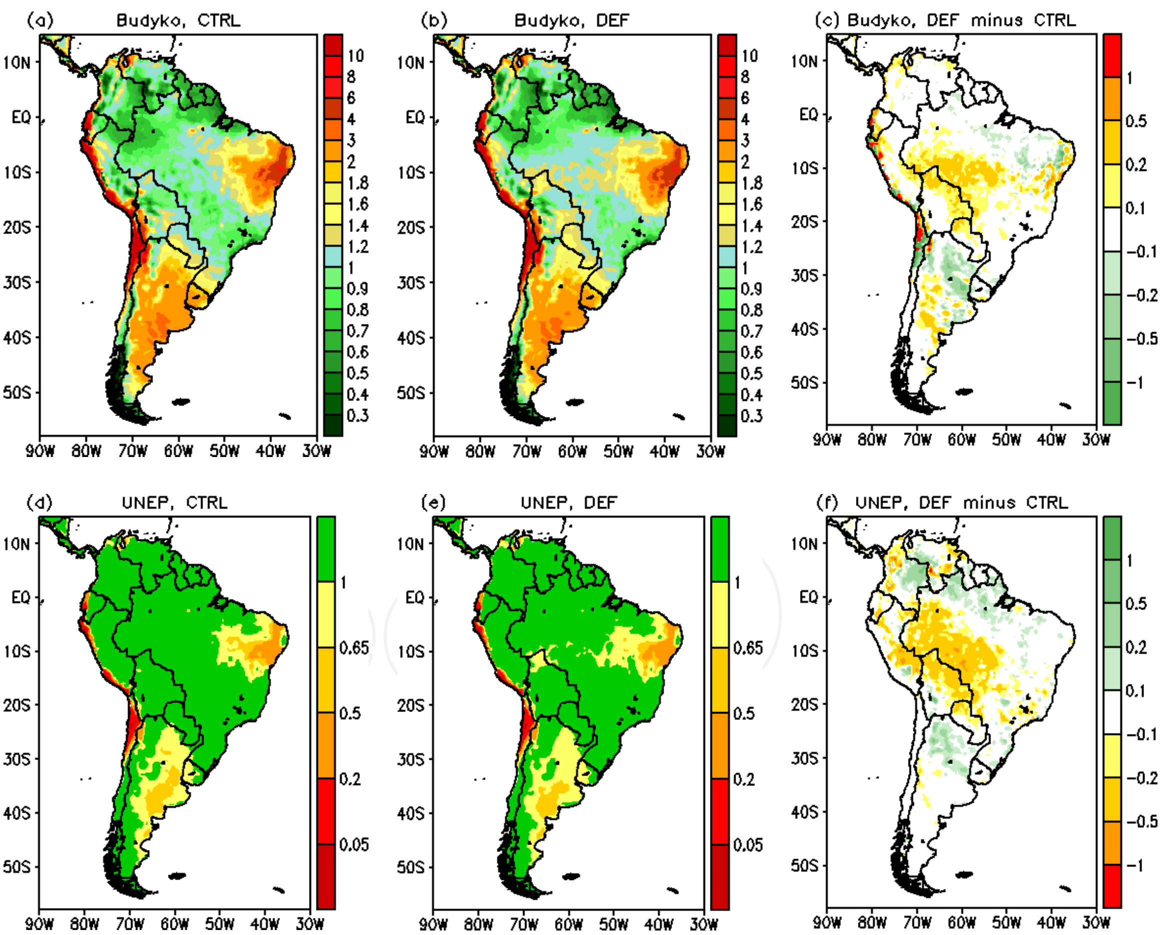

Figure 3. Distribution of aridity using Budyko index: a) control experiment, b) deforestation experiment and c) changes (deforestation minus control); and using UNEP index: d) control experiment, e) deforestation experiment and f) changes (deforestation minus control).

The changes (perturbed minus control) in the net surface radiation, precipitation, evapotranspiration and surface temperature due to deforestation are shown in Table 2. There is a decrease of the mean net surface radiation (-7.8 W m^{-2}) due to the increase of the land surface albedo; the mean evapotranspiration and precipitation decrease (-0.25 mm day^{-1} and-0.54 mm day^{-1}, respectively). The sign of the change in the surface temperature is different in the three regions of Amazonia. The mean surface temperature decreases in the north and central areas (-0.3C and-0.2C, respectively) and increases in the south region (+0.1C). As shown in Fig. 4a, the surface temperature increases by+0.6C in the south Amazonia and decreases by-0.9C in the north Amazonia. Since the higher decrease in evapotranspiration occurs in the south Amazonia it seems that the effect of the reduction in evapotranspiration in this region overcomes that of the increase of albedo while in the other two regions this does not occur. This leads to an increase of the temperature in the south Amazonia and a decrease in the north and central Amazonia. The changes in surface temperature in the three areas of Amazonia are in good agreement with the changes in the aridity given by Budyko index which indicates a high increase of the aridity in the south region (with a consequent increase in the surface temperature) while in the other two areas a decrease of aridity (and a consequent decrease in the surface temperature) is noted (Fig. 3c). The UNEP index also indicates a high increase of aridity in the south Amazonia and a decrease in the north Amazonia. However, differently from the Budyko index an increase of the aridity in the central region is noted.

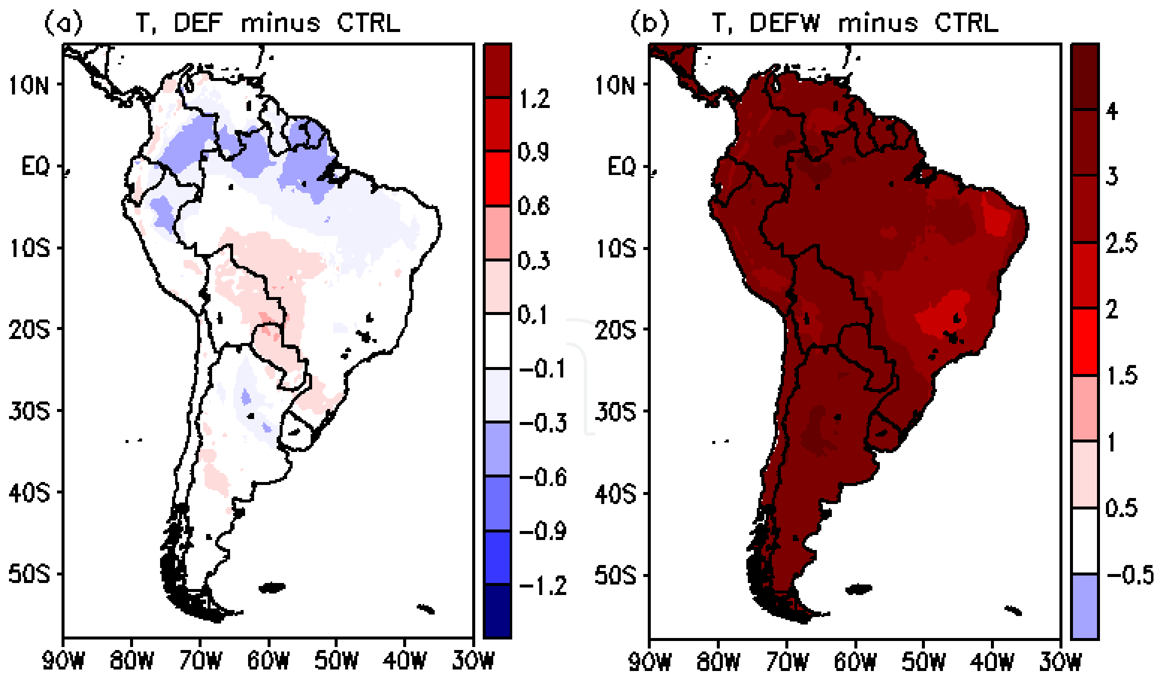

Figure 4. Changes in the surface temperature: a) deforestation minus control and b) deforestation plus pseudo-warming minus control. Units, ºC.

Experiment		Δ R (W m^{-2})	Δ P (mm day^{-1})	Δ E (mm day^{-1})	Δ T (C)
Deforestation	North Amazonia	-7.8	-0.10	-0.16	-0.3
	Central Amazonia	-7.8	-0.43	-0.24	-0.2
	South Amazonia	-7.7	-1.08	-0.36	+0.1
	Mean	-7.8	-0.54	-0.25	-0.1
Deforestation plus pseudo-global warming	North Amazonia	-1.7	-1.27	-0.48	+3.6
	Central Amazonia	-4.3	-0.57	-0.42	+3.6
	South Amazonia	-1.9	+0.53	-0.22	+3.3
	Mean	-2.6	-0.44	-0.37	+3.5

Table 2. Changes (perturbed minus control) in the surface net radiation (W m^{-2}), precipitation (mm day^{-1}), evapotranspiration (mm day^{-1}) and surface temperature (°C) for the experiment of deforestation and deforestation plus pseudo-warming.

3.2. Effect of deforestation including pseudo-warming

Figure 5 shows the distribution of aridity for the experiment considering deforestation together with pseudo-warming and the change (deforestation plus pseudo-warming minus control) using the Budyko and UNEP indices. From Figs. 5a and 3b it can be seen that when the pseudo-warming scenario is taken into account the areas humid regime (forest) are replaced by semi-humid regime (savanna) northwards compared with the case of deforestation only. This leads to an increase of the aridity in this region. In the south Amazonia there is a decrease of the aridity, as shown in Fig. 5b. As can be seen in Table 1 the aridity increases 20% and 7.6% relative to the control in the north and central Amazonia, respectively, while in the case of only deforestation there is a decrease of aridity (4% and 1.1%, respectively). In the south Amazonia the aridity is decreased by 10% compared to the control while it increases in the case with only deforestation (22%).

Figures 5c and 5d show that in the case of the UNEP index there is a general increase of the aridity in the three regions in the deforestation plus pseudo-warming experiment compared with the control experiment. The increase of the aridity is higher in the north Amazonia (37.6%) followed by the central (28%) and south (10.3%) Amazonia. From Figs. 5d, 3f and Table 1 it can be seen that the aridity increases largely in the north Amazonia when the pseudo-warming is taken into account while it decreases in the case with only deforestation. Although in the two experiments there is an enhancement of the aridity in the central Amazonia the increase is much higher when the pseudo-warming is included. On the other hand the increase of the aridity in the south Amazonia is higher in the case of only deforestation.

It can be seen from above that the changes in the distribution of aridity due to deforestation together with pseudo-warming using Budyko and UNEP indices are in agreement. These

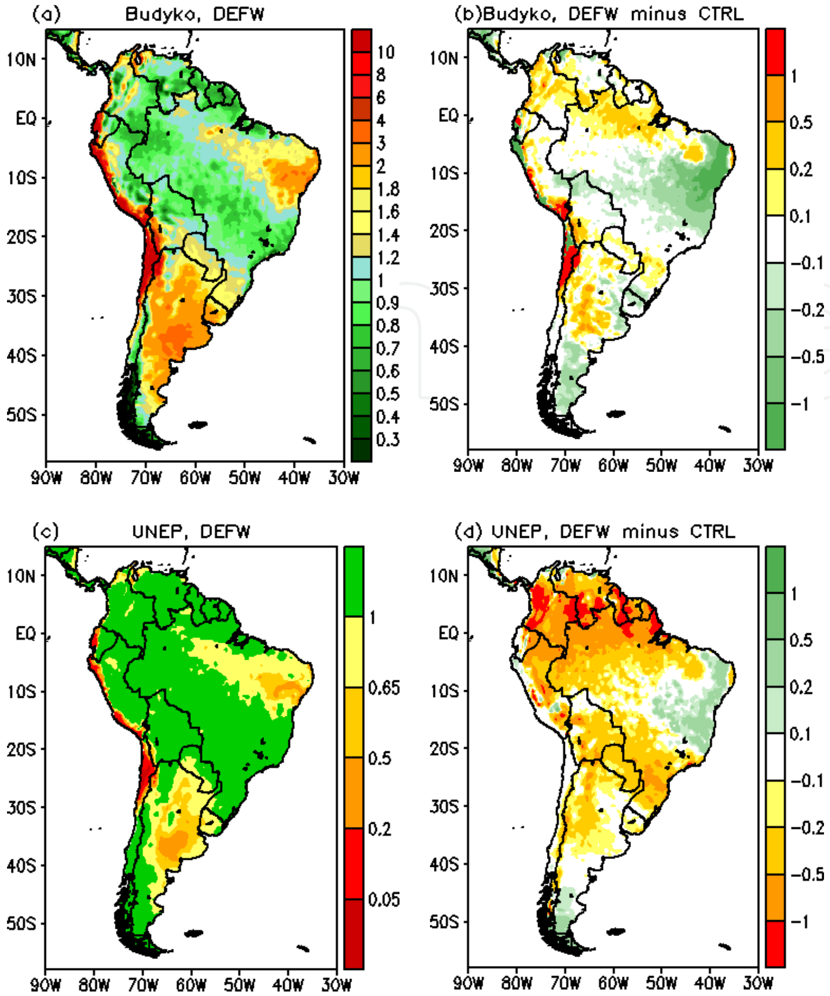

Figure 5. Distribution of aridity using Budyko index: a) deforestation plus pseudo-warming experiment and b) changes (deforestation plus pseudo-warming minus control); and using UNEP index: c) deforestation plus pseudo-warming experiment and d) changes (deforestation plus pseudo-warming minus control).

changes are higher compared to the case with only deforestation. On the other hand, the results diverge in the south Amazonia: the use of Budyko index indicates a decrease of aridity while the UNEP index suggests an increase.

Table 2 shows that the main changes in the Amazonia (an average over the three regions) are a warming of 3.5C and decreases in evapotranspiration (0.37 mm day^{-1}) and precipitation (0.44 mm day^{-1}) relative to the control. It can be seen from Table 2 that the inclusion of the pseudo-warming largely increases the changes in the surface temperature due to deforestation. However, deforestation may have a significant effect locally. As seen in Figs. 4a and 4b, the changes in the surface temperature due to deforestation may reach+0.6C in the south Amazonia, which correspond to 15% of the higher changes when the pseudo-warming is included (+4C). The increase in the surface temperature when the pseudo-warming is taken into account together is due mainly to the lower reduction in the net surface radiation in addition to the higher reduction in evapotranspiration. The changes in the surface temperature are large in the three regions of Amazonia. These changes are in good agreement with the changes in the

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aridity given by the UNEP index which indicate an increase of the aridity (and consequent increase of the surface temperature) in the three regions compared to the control (Table 1). The increase of the aridity is higher in the north Amazonia followed by the central and south Amazonia in agreement with the change in the surface temperature in these regions. The Budyko index also shows a higher increase of the aridity in the north Amazonia followed by the central Amazonia. However, in the south Amazonia an increase of the aridity is noted.

The present results agree with some studies with GCMs [8, 9, 10, 11, 36, 37] and with simple mechanistic models [5, 6, 38] which suggest that tropical South America is a region where significant portions of rainforest may be replaced by savanna (grassland) in future due to the global warming. The results also showed that the warming due to deforestation may have important effect locally; on the other hand when the effect of the global warming is included, the change of tropical forest areas of Amazonia by savanna may be enhanced compared with the present climate. This reinforces the hypothesis that due to global warming the process of savannization of tropical forest of Amazonia can be accelerated.

4. Conclusions

In this paper the relative roles of the land surface degradation in Amazonia and global warming on the regional climate and aridity were investigated using the RegCM4 model. Two experiments were performed: 1) deforestation and 2) deforestation together with global warming. The distribution of the aridity over South America, particularly over the tropical region, was obtained using the dryness index of Budyko and the UNEP aridity index. The results showed that the deforestation may have large influence locally (15% of the warming when the pseudo-warming was included together). The higher increase of the surface temperature occurred in the south Amazonia (+0.6C) whereas in the north and central Amazonia a decrease of temperature was noted (higher decrease of-0.9C). The changes in the distribution of aridity due to deforestation using Budyko and UNEP indices showed a very good agreement. It was suggested that there was an increase of 22% in the drying in the south Amazonia and a decrease of 3%-4% in the north Amazonia.

When the pseudo-warming was taken into account the changes in surface temperature were largely enhanced in relation to the deforestation case and the warming occurred in the entire Amazonia (higher increase of+4C). The changes in the distribution of aridity using Budyko and UNEP indices were similar. The aridity increased in most of Amazonia compared to the deforestation case. The higher increase occurred in the north Amazonia (20% for the Budyko index and 37.6% for the UNEP index).

Thus, the present study indicated that the global warming may affect the distribution of aridity over the tropical region of Amazonia, where significant portions of rain forest may be replaced by nonforested areas and this corroborates the hypothesis that the process of savannization of the tropical forest of Amazonia can be accelerated in future.

Acknowledgements

Thanks are due to Dr. Erika Coppola and the ICTP group for providing the RegCM4 code. Thanks are also due to Dr. V. Brahmananda Rao for going through the manuscript.

Author details

Sergio H. Franchito*, J. P. R. Fernandez and David Pareja

*Address all correspondence to: sergio.franchito@cptec.inpe.br

Centro de Previsão de Tempo e Estudos Climáticos, CPTEC, Instituto Nacional de Pesquisas Espaciais, INPE, SP, Brazil

References

[1] Nobre C A, Sellers P J, Shukla J. Amazonian deforestation and regional climate change. Journal of Climate 1991; 4: 957– 988.

[2] Sampaio G, Nobre C A, Costa M H, Satyamurty P, Soares-Filho B S. Regional climate change over eastern Amazonia caused by pasture and soybean cropland expansion. Geophysical Research Letters 2007; 34: L17709.

[3] Medvigy D, Walko R L, Avissar R. Effects of deforestation on spatiotemporal precipitation in South America. Journal of Climate 2011; 24: 2147-2163.

[4] Varejão-Silva M A, Franchito S H, Rao V B. A coupled biosphere-atmosphere climate model suitable for use in climatic studies due to land surface alterations. Journal of Climate 1998; 11: 1749–1767.

[5] Franchito S H, Rao V B, Fernandez J P R. Tropical land savannization: impact of global warming. Theoretical and Applied Climatology 2012; 109: 73-79.

[6] Moraes E C, Franchito S H, Rao V B. Amazonian deforestation: impact of global warming on the energy balance and climate. Journal of Applied Meteorology and Climatology 2013; 52: 521-530.

[7] Gash, J H C, Nobre C A. Climatic effects of Amazonian deforestation: some results from ABRACOS. Bulletin of the American Meteorological Society 1977; 78: 823–830.

[8] Cox P M, Betts R A, Collins M, Harris P P, Huntingford C, Jones C D. Amazonian forest dieback under climate-carbon cycle projections for the 21st century. Theoretical and Applied Climatology 2004; 78: 137– 156, doi:10.1007/s00704-004-0049-4.

[9] Betts R A, Cox P M, Collins M, Harris P P, Huntingford C, Jones C D. The role of ecosystem-atmosphere interactions in simulated Amazonian precipitation decrease and forest dieback under global climate warming. Theoretical and Applied Climatology 2004; 78: 157–175.

[10] Salazar R F, Nobre C A, Oyama M D. Climate change consequences on the biome distribution in tropical South America. Geophysical Research Letters 2007; 34: L09708, doi:10.1029/2007GL029695.

[11] Malhi Y, Aragão L O C, Galbraith D, Huntingford C, Fisher R, Zelazowski P, Stich S, McSweenney C, Meier P. Exploring likelihood and mechanism of a climate-change-induced dieback of the Amazon rainforest. Proc. Natl. Acad. Sci. USA. Special feature: Sustainability Science 2009. available at: http://www.pnas.org_doi_10.1073.pnas.0804619106.

[12] Maynard K, Royer J.-F. Effects of "realistic" land-cover change on a greenhouse-warmed African climate. Climate Dynamics 2004; 22: 343–358.

[13] Voldoire A. Quantifying the impact of future land-use changes against increases in GHG concentrations. Geophysical Research Letters 2006; 33: L04701, doi: 10.1029/2005GL024354.

[14] Feddema J J, Oleson K W, Bonan G B, Mearns L O, Buja L E, Meehl G A, Washington W M. The importance of land-cover change in simulating future climates. Science 2005; 310: 1674–1678.

[15] Giorgi F, Marinucci M R, Bates G T. Development of a second-generation regional climate model (RegCM2). Part I: Boundary-layer and radiative transfer process. Monthly Weather Review 1993; 121: 2794–2812.

[16] Giorgi F, Marinucci M R, Bates G T, Decanio G. Development of a second-generation regional climate model (RegCM2). Part II: Convective process and assimilation of lateral boundary conditions. Monthly Weather Review 1993; 121: 2814–2831.

[17] Roads J O, Chen S-C. Surface water and energy budgets in the NCEP regional spectral model. Journal of Geophysical Research 2000; 105: 29539–29549.

[18] Chen S-C, Wu M-C, Marshall S, Juang H-M, Roads J O. 2 x CO_2 eastern Asia regional responses in the RSM/CCM3 modelling system. Global and Planetary Change 2003; 37: 277–285.

[19] Giorgi F, Coppola E, Solmon F et al. RegCM4: model description and preliminary tests over multiple CORDEX domains. Climate Research 2012; 52, 7-29.

[20] Schar C, Christoph F, Lutthi D, Davies H C. Surrogate climate-change scenarios for regional climate models. Geophysical Research Letters 1996; 23: 669-672.

[21] Budyko M I. The Heat Balance of the Earth's Surface. U.S. Department of Commerce, Washington D.C. 1958; 259 pp, translated by N.A. Stepanova.

[22] UNEP 1992: World Atlas of Desertification. Edward Arnold, London, UK.

[23] Grell G A, Dudhia J, Stauffer D R. A description of the fifth generation Penn State/ NCAR Mesoscale Model (MM5). National Center for Atmospheric Research Technical Note NCAR/TN-398+STR, 1994, NCAR, Boulder, CO.

[24] da Rocha R P, Cuadra S V, Reboita M S, Kruger L F, Ambrizzi T, Krusche N. Effects of RegCM3 parameterizations on simulated rainy season over South America. Climate Research 2013; 52: 253-265.

[25] Giorgi F, Jones C, Asrar G. Addressing climate information needs at the regional level: the CORDEX framework. WMO Bulletin 2009; 58: 175-183.

[26] Dee D P and coauthors. The ERA-Interim reanalysis: configuration and performance of the data assimilation system. Quarterly Journal Royal Meteorological Society 2011; 137: 553-597.

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

[28] Sun Y I, Yan X D, Xie D T. Analysing vegetation-climate interactions in China based on Budyko's indices. Research Science 2006; 28: 23-29 (in Chinese with English abstract).

[29] Gao X, Giorgi F. Increased aridity in the Mediterranean region under greenhouse gas forcing estimated from high resolution simulations with a regional climate model. Global and Planetary Change 2008; 62: 195-209.

[30] Thornthwaite C W. An approach toward a rational classification of climate. Geographic Review 1948; 38: 55–94.

[31] Pareja D. Sensitivity experiments over Brazil considering global warming scenarios using a regional climate model. MSc thesis. INPE-17254-TDI/2083. Sao Jose dos Campos 2013 (In Portuguese).

[32] Reynolds R W, Rayner N A, Smith T M, Stokes D C, Diane C, Wang W. An improved in situ and satellite SST analysis for climate. Journal of Climate 2002; 15: 1609-1625.

[33] Randall D A and coauthors. Climate models and their evaluation. In: Climate Change 2007: The physical Sciences Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press 2007.

[34] Im E, Coppola E, Giorgi F, Bi X. Local effects of climate change over the Alpine region: A study with a high resolution regional climate model with a surrogate climate change scenario. Geophysical Research Letters 2010; 37: L05704, doi: 10.1029/2009GL041801.

[35] Winter J M, Eltahir E A B. Modeling the hydroclimatology of the midwestern United States. Part 2: future climate. Climate Dynamics 2012; 38: 595-611.

[36] Scholze M, Knorr W, Arnell N W, Prentice I C. A climate change risk analysis for world ecosystems. Proc. Natl. Acad. Sci. U. S. A. 2006; 103(35), 13,116–13,120.

[37] Cook K H, Vizy K H. Effects of Twenty-First-Century Climate Change on the Amazon Rain Forest. Journal of. Climate 2008; 21: 542–560.

[38] Franchito S H, Rao V B, Moraes E C. Impact of global warming on the geobotanic zones: an experiment with a statistical-dynamical climate model. Climate Dynamics 2011; 37: 2021-2034.