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Water budget changes in the Amazon basin under RCP 8.5 and deforestation scenarios

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ABSTRACT: We used climate models to assess the effects of 2 distinct anthropogenic forcings on the water budget in the Amazon basin: (1) increasing global greenhouse gases under the RCP8.5 scenario, and (2) land cover change caused by deforestation. The Eta regional climate model, driven by the Brazilian Earth System Model version 2.5 (BESM 2.5), was used to simulate the climate response under the RCP8.5 scenario and due to deforestation throughout the 21st century. Changes in energy and water budgets led to an increase in temperature that reached 5°C throughout the basin. In the RCP8.5 scenario, moisture convergence, precipitation and evapotranspiration all decreased. In this scenario, the positive feedback mechanism was predominant, as the reductions in evapotranspiration and moisture convergence acted in the same direction to reduce precipitation. In the future deforestation scenarios, reductions in precipitation were even stronger. In this case, the negative feedback mechanism predominated, in which the relative reduction in evapotranspiration was greater than the reduction in precipitation, leading to an increase in moisture convergence over the region. Changes in temperature and the water cycle were intensified in the future deforestation scenarios. These results show that the 2 anthropogenic factors can change the water budget and cause an imbalance in the climate–biome system in the Amazon basin, highlighting the need for public conservation policies to halt the increase in environmental degradation in the Amazon basin and to reduce greenhouse gases emissions due the burning of fossil fuels.

KEY WORDS: Amazon Basin · Anthropogenic scenarios · Deforestation · Water budget · Climate Modeling

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1. INTRODUCTION

The Amazon is the largest continuous area of tropical rainforest on planet. The large annual amount of precipitation (2300 mm yr^{-1}) makes the region an important source of heat and moisture for the atmosphere, as well as fresh water for the oceans through the substantial annual fluvial discharge (220 000 m^3 s^{-1}), which represents 15% of the total river discharges in the world oceans (Marengo 2006, Marengo et al. 2018). The Amazon basin behaves as a moisture sink for the atmosphere, as the precipitation rate is higher than the evapotranspiration rate. This behavior is explained by the intense recycling of

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water in the tropical forest (Rocha et al. 2015), as well as by the transport of moisture from the tropical Atlantic into the Amazon region (Malhi et al. 2008, Nepstad et al. 2008, Satyamurty et al. 2013). The Amazon region acts as a source of energy through its intense evapotranspiration and release of latent heat in the middle and upper troposphere through tropical convective clouds, contributing to the generation and maintenance of atmospheric circulation at regional and global scales (Artaxo et al. 2005, Fearnside 2005, Marengo 2006, Malhi et al. 2008).

In the regional context, the Amazon forest plays a fundamental role in determining the hydrological regime both in the basin itself, as a result of water recycling, and in other regions of South America by means of moisture transport by the low level jet (Arraut & Satyamurty 2009, Rocha et al. 2015). However, the Amazon basin is vulnerable to the variability and changes in the climatic system, due to both natural variations associated with the Pacific and Atlantic Ocean modes of variability (El Niño Southern Oscillation, Pacific Decadal Oscillation and Atlantic Multidecadal Oscillation), and also due to anthropogenic changes caused by global increases in greenhouse gases (GHGs) and changes in land use and cover, including deforestation, agricultural activities and urbanization (Marengo et al. 2012, Drumond et al. 2014, Espinoza et al. 2014, Zhang et al. 2015, Marengo & Espinoza 2016, Sorribas et al. 2016, Alves et al. 2017, Aragão et al. 2018, Kalamandeen et al. 2018, Sorí et al. 2018). Such natural and/or anthropogenic changes can affect Amazonian ecosystems by reducing the capacity for carbon sequestration, by modifying the regional hydrological cycle. These changes can consequently cause damage to the primary sectors of local economies, such as agriculture, river navigation and energy generation, and can affect vulnerable people and communities of the Amazon region (Doughty et al. 2015).

The projections of climate change from the simulations of the global climate models of the Intergovernmental Panel on Climate Change — Fifth Assessment Report (AR5) show a reduction and increase in rainfall in different regions of South America by the end of the 21st century, with a high degree of uncertainty in the Amazon region (Stocker et al. 2013). However, the main limitation of global models is their low spatial grid resolution, which limits the representation of sub-grid physical processes and mesoscale forcings (complex topography, surface heterogeneity and large lakes and rivers), which affect the accuracy of temperature variation and precipitation at the regional scale (McPherson 2007). Another worrying factor for climate variability and change is deforestation in the Amazon basin. Considering historical data, total deforestation in the Amazon up to 2019 was 446 000 km^2, corresponding to 16 % of the Brazilian Amazonian forest (INPE 2017). This corresponds to an average rate of 14 300 km^2 yr^{-1}. In the last decades, the effects of deforestation on the climate of the Amazon basin using global and regional circulation models have been evaluated (Correia et al. 2007, D'Almeida et al. 2007, Nobre et al. 2009, Silva et al. 2016, Alves et al. 2017, Silveira et al. 2017, Llopart et al. 2018). Llopart et al. (2018) used the Common Land Model (CLM 4.5), coupled with the Regional Climate Model (RegCM4), over the Coordinated Regional Climate Downscaling Experiment (CORDEX) in order to evaluate the effects of deforestation in the Amazon region. They noticed a dipole pattern in the distribution of precipitation over the basin, with reductions in the western portion (8 %) and an increase in the eastern sector (8.3 %). Silva et al. (2016) evaluated the effects on the circulation and thermodynamics of the atmosphere due to deforestation in the Amazon basin using the RegCM3 regional model. The authors showed that the weakening of the upward movement in the mid-upper troposphere is the main mechanism that explains the reduction in precipitation for the deforestation scenario in the Amazon basin. Using the regional Eta model, Marengo et al. (2012) evaluated future climate projections (Special Report on Emissions Scenarios [SRES] A1B) in South America. The authors found an intense reduction in rainfall in most of the Amazon basin in the late 21st century. Using scenarios of changes in land use and future climate projections (SRES A2), Guimberteau et al. (2017) observed an increase in air temperature (3.3°C), evapotranspiration (5 %), precipitation (8.5 %) and surface runoff (14 %) in the Amazon basin.

Overall, these different studies have shown that deforestation in the Amazon can lead to significant impacts on energy, water and carbon budgets, producing an increase in surface temperature and a reduction in regional precipitation. Given the synergy of regional impacts resulting from changes in land use and the effects of global climate change, a major issue raised in the scientific community is in what ways increasing GHGs and land use changes can modify water budgets in the Amazon basin.' In order to answer this question, we evaluated the impacts of increased GHGs and of deforestation on the water budget in the Amazon basin. This was done by integrating the Eta Regional Climate Model driven by the Brazilian Earth System Model Ocean-Atmosphere version 2.5 (BESM-OA 2.5), using the

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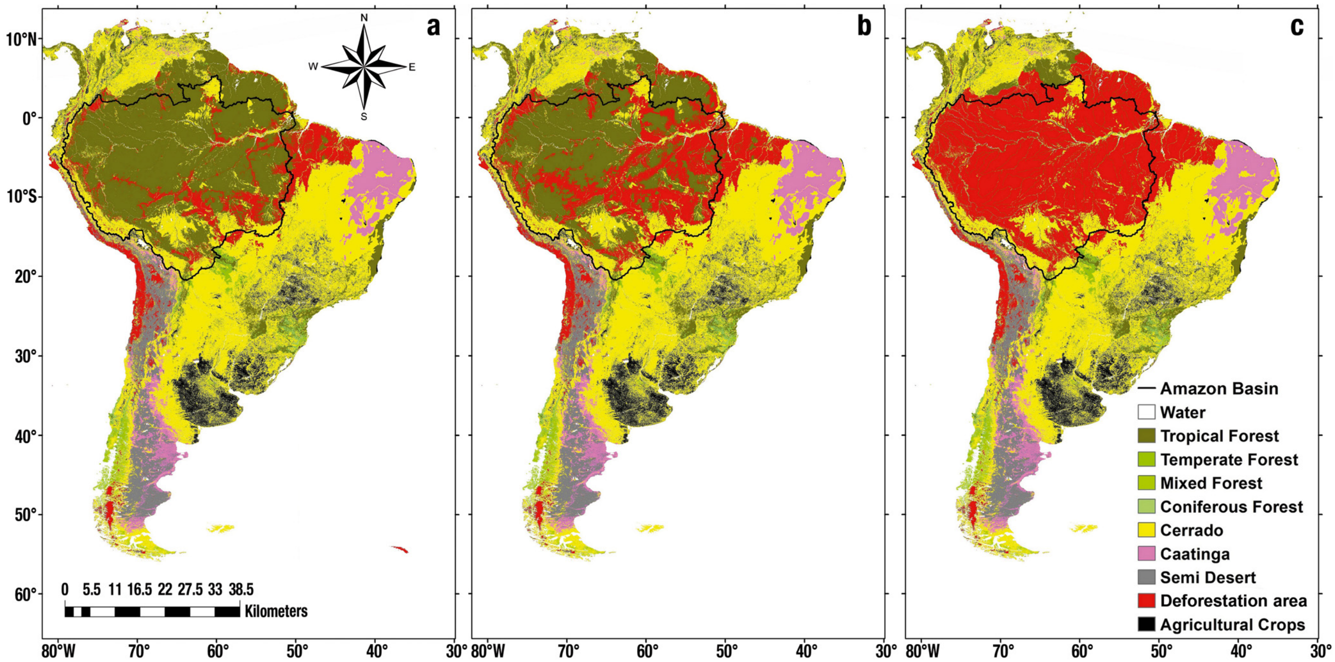

Fig. 1. Vegetation cover scenarios used in simulations with the Eta regional model. (a) Vegetation map prepared by the ProVeg Project with deforested areas (base year 2015); and scenarios projected for the year (b) 2050 and (c) 2100. Both scenarios elaborated by the DINAMICA model. Resolution: 1 × 1 km

representative concentration pathway 8.5 (RCP8.5) emission scenario (IPCC AR5) and deforestation scenarios in the Amazon basin.

2. DATA AND METHODS

2.1. Emission scenarios and land use changes

In this study, we used the emission scenario based on the RCP8.5 of the IPCC AR5 (Van Vuuren et al. 2011a,b). The emission scenarios (RCPs) represent different GHG concentration trajectories in the future climate. In these scenarios, the possible changes in the earth–atmosphere system are conceived by the values of the radiative forcings which comprise the values 2.6, 4.5, 6.0 and 8.5 W m^{-2}. Three land use maps for the Amazon basin were used: (1) the current vegetation map (base year of 2015); (2) the deforested map projected for 2050; and (3) the deforested map projected for 2100 (Fig. 1). For the current vegetation, we considered the map produced by the ProVeg Project (Sestini et al. 2002) in combination with a map from the project 'Estimate of Gross Deforestation of the Amazon' — PRODES-DIGITAL (INPE 2017), which shows the deforested areas as of 2015. The scenarios of future deforestation for the years 2050 and 2100 were provided by the landscape dynamics model DINAMICA (Soares Filho et al. 2004). The DINAMICA model is a spatial simulation model of the cellular automaton type designed to simulate the dynamics of changes in land use and coverage in the Amazon basin, mainly in areas occupied by small farms. The model incorporates decision processes based on land use practices adopted by Amazon settlers, and is parameterized by the assimilation of data obtained by remote sensing. Future deforestation projections produced by DINAMICA show an increase of 42% in the deforested area in the 2050 scenario in relation to 2015. In the 2100 scenario, the deforested area is expected to increase to 75% of the total area. The eastern and southeastern regions of the Amazon are the most altered (the so-called 'arc of deforestation'). The degraded pasture biome represents deforestation in the Amazon basin. The physical and physiological properties of the vegetation and soil for the major modeled biomes are listed in Table 1.

2.2. Description of models and numerical integration strategy

In order to evaluate the impacts of increased GHGs and of deforestation on the water budget, numerical simulations were performed using the Eta Regional Model (limited area) run with the initial and bound-

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Table 1. Biophysical parameters used according to vegetation type

Parameters	Forest	Pasture	Savanna
Albedo	0.13[a]	0.18[a]	0.18[b]
Emissivity	0.95	0.96	0.97
Leaf area index (LAI)	5.2[a]	2.7[a]	1.0[b]
Fraction of vegetation cover (V_{frac})	0.98[c]	0.85[c]	0.50
Seasonal variation in V_{frac}	0.05	0.10	0.30
Roughness length (m)	2.35[a]	0.05[a]	1.20[b]
Displacement of the zero plane (m)	28.4[a]	0.3[a]	10.0[b]
Depth of roots (m)	4.0[a]	1.0	2.0
Stomatal conductance (mm s^{-1})	0.0035[d]	0.0010[d]	0.0020[d]

The indexes were derived from the following studies: [a]Wright et al. (1995); [b]Miranda et al. (1997); [c]Silva Dias & Regnier (1996); [d]Freitas (1999)

ary conditions from the BESM-OA 2.5, via the technique of dynamic downscaling. The BESM-OA 2.5 (Capistrano et al. 2018, Veiga et al. 2019) was developed by the Brazilian National Institute for Space Research (INPE). The BESM-OA 2.5 is an Eulerian spectral model with T62 triangular truncation and 28 vertical levels. The BESM-OA 2.5 was used to force the Eta Regional model for the present (baseline) period and end-of-century climate conditions under the RCP8.5 emission scenario. The model is the result of coupling the Center for Weather Forecast and Climate Studies (CPTEC/INPE) Brazilian Atmospheric Model BAM (Figueroa et al. 2016) and the Geophysical Fluid Dynamics Laboratory (GFDL) Modular Ocean Model version 4p1 (Griffies et al. 2009) via the Flexible Modular System (FMS), also from GFDL. The model uses a sigma vertical coordinate, and topography is treated in a spectral way (Bonatti 1996). The physical parameters include the Simplified Simple Biosphere Model (SSiB) (Xue et al. 1991), the turbulence scheme of the planetary boundary layer is the Mellor-Yamada 2.0 (Mellor & Yamada 1982), the deep convection scheme follows Grell & Dévényi (2002), and the shallow convection scheme follows Tiedtke (1984). The short-wave and long-wave radiation schemes are from Tarasova et al. (2007) and Harshvardhan et al. (1987), respectively.

The Eta regional model was modified to carry out long-term integrations (Pesquero et al. 2010, Chou et al. 2012, 2014a,b). The model uses the eta vertical coordinate (Mesinger 1984), which is a step-terrain coordinate. The horizontal surfaces of the eta coordinate make them appropriate to operate in steep mountain regions such as the Andes Mountains in South America. The precipitation is produced by the Betts-Miller-Janji cumulus parameterization scheme (Janji 1994) and by the Zhao cloud microphysics scheme (Zhao et al. 1997). The radiation is treated by the Lacis & Hansen (1974) short-wave scheme and Fels & Schwarzkopf (1975) long-wave scheme. Land surface processes are treated by the NOAH scheme (Ek et al. 2003), which contains 4 soil layers for temperature and humidity, as well as 12 types of vegetation and 7 types of soil texture. In this study, the model was configured with a horizontal resolution of 20 km and 38 vertical levels. The evapotranspiration in the Eta model is calculated using the Penman-Monteith formula, and runoff (R) is estimated from the difference between precipitation (P) and evapotranspiration (E), as $R = (P - E)$ = surface runoff. The first experiment included the current vegetation map with deforestation for the year 2015 and the present climate from BESM-OA 2.5. This experiment consisted of a continuous 46 yr integration initialized on 1 January 1960, 00:00 h UTC. The carbon dioxide (CO_2) concentration remained constant at 330 ppm during integration. In the future climate and the second, third and fourth experiments we used the emissions scenario of RCP8.5 produced by BESM-OA 2.5, the vegetation map of 2015 and the deforestation scenarios for the years 2050 and 2100, respectively. For the future climate, the integrations were carried out continuously for the period 2071–2100 (31 yr). The lateral boundary conditions are updated with variables of the BESM-OA 2.5 model at each 6 h interval. The model updates the equivalent concentration of CO_2 every 3 yr. Sea surface temperature (SST), initial soil moisture and soil temperature are obtained from BESM-OA 2.5. The SST is updated daily in the regional model Eta. Downscaling simulations are referred to as Eta-BESM-OA, where the Eta model is forced by BESM-OA 2.5.

3. RESULTS AND DISCUSSION

The evaluation of the performance of the model was based on comparisons between Eta precipitation simulations of the baseline period (1979–2005) and the Era-Interim reanalysis and observations data (Dee et al. 2011), Merge Analysis of Precipitation (CMAP) (Xie & Arkin 1996) and the Global Precipitation Climatology Project (GPCP) (Xie et al. 2003). The changes in the climate resulting from the RCP8.5 scenario and the future deforestation scenarios for 2050 and 2100 are assessed with respect to the baseline period 1979–2005. The assessment is based mainly on the components of the water budget (precipitation, evapotranspiration, moisture convergence and runoff) and temperature in the Amazon basin.

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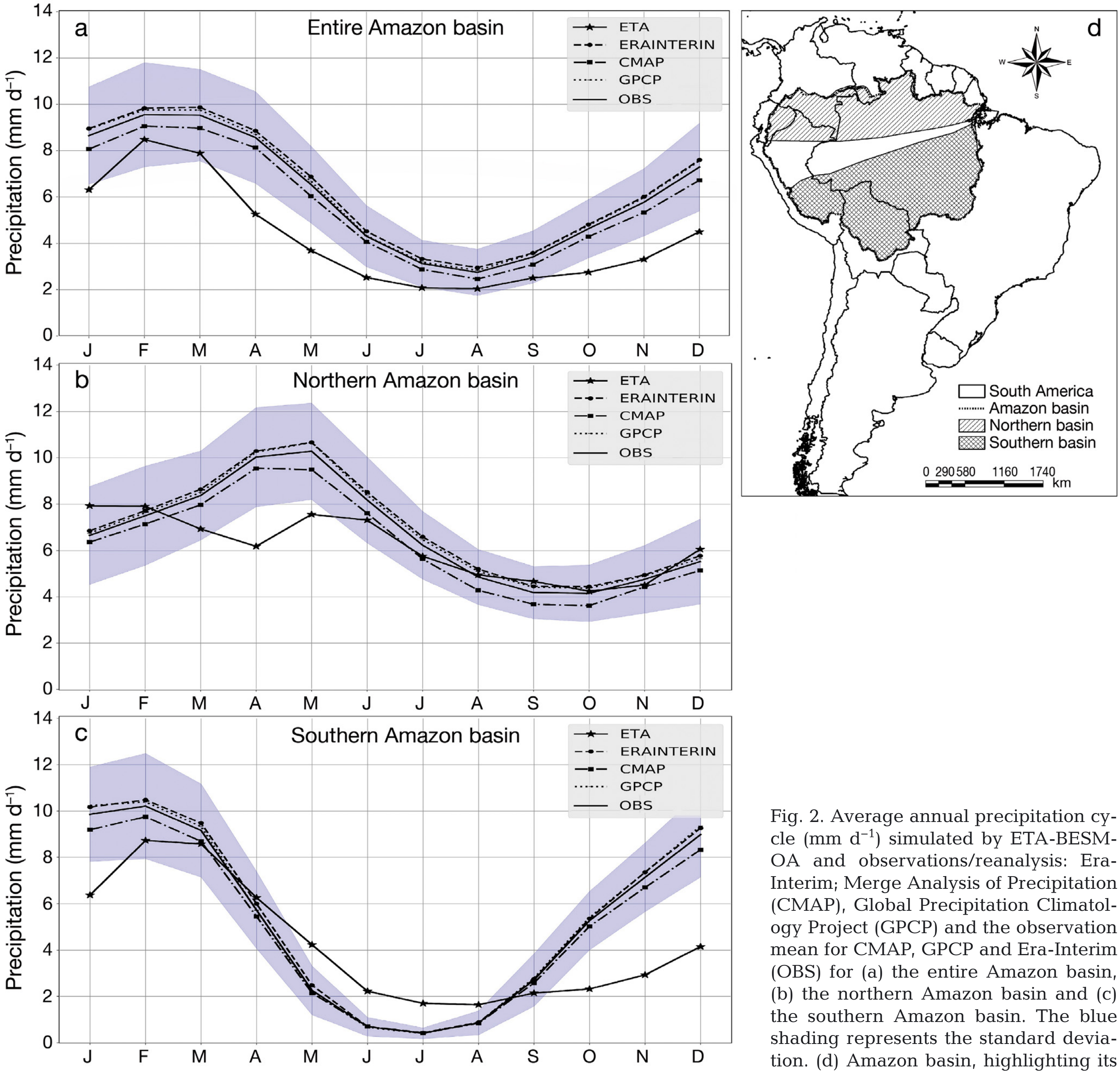

Fig. 2. Average annual precipitation cycle (mm d^{-1}) simulated by ETA-BESM-OA and observations/reanalysis: Era-Interim; Merge Analysis of Precipitation (CMAP), Global Precipitation Climatology Project (GPCP) and the observation mean for CMAP, GPCP and Era-Interim (OBS) for (a) the entire Amazon basin, (b) the northern Amazon basin and (c) the southern Amazon basin. The blue shading represents the standard deviation. (d) Amazon basin, highlighting its northern and southern basins

The annual precipitation cycle projected by the Eta-BESM-OA simulations and observations with respect to the reference period is shown in Fig. 2. In general, the Eta-BESM-OA model was able to represent the seasonality in precipitation over the basin, presenting the highest values in February–March and the lowest in August–September, in agreement with the observations. However, the model underestimates precipitation throughout the period mainly in the months during autumn and spring. The annual simulated precipitation cycle for Eta-BESM-OA and observations show some differences between the northern and southern parts of the basin, with greater seasonal amplitude in the southern portion of the basin (Fig. 2b–d). This behavior is due to the characteristics of the monsoon regime in South America and the seasonal shift of the Intertropical Convergence Zone (ITCZ) throughout the year. In regional terms, the simulations better reproduced the annual precipitation cycle in the southern portion of the basin but had difficulties in the northern portion, mainly due to the difficulty in correctly simulating the intensity and positioning of the ITCZ in the Atlantic Ocean.

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3.1. Changes in 2 m air temperature and evapotranspiration

Fig. 3 shows the seasonal mean air temperature at 2 m simulated by the Eta-BESM-OA for the reference period (1979–2005) and the future period changes (2071–2100) under the RCP8.5-only scenario and with the inclusion of deforestation scenarios for the period 2050 and 2100. The changes are presented for wet (Dec–Feb) and dry (Jun–Aug) periods. A small temperature variation over the Amazon basin in the current period occurs due to the homogeneous and intense availability of solar energy during the annual cycle in this region. Under the RCP8.5-only scenario, significant changes in temperature over the entire South American continent are projected (Fig. 3b,f). The most intense changes are projected in the central and northern basin, where temperature increases by about 3–5°C. Changes in the surface energy availability (net radiation) are followed by an increase in the sensible heat flux and in the ground heat, which leads to temperature increases in the basin. However, these changes are intensified when future deforestation scenarios are included. In the 2050 (2100) deforestation scenario, the increase in temperature ranged from 4–6°C (5–7°C).

The temperature increase in the deforestation scenario is due to the reduction in evapotranspiration (Fig. 4) and reduction in the roughness length (Table 1), since the roughness plays a fundamental role in modulating the turbulent fluxes of heat and humidity between the surface and the free atmosphere. Evapotranspiration reduces by about 6% (2015), 12% (2050) and 20% (2100) in the three 30 yr timeslices and in all scenarios, which shows more significant changes in the dry season and for the 2100 scenario. The reduction of the roughness length, from 2.55 m in the forest down to 0.02 m in the degraded pasture, weakens the turbulent transfer of energy from the surface. Therefore, higher temperatures are required to remove excessive energy from the surface. The lower leaf area index and the reduced capacity to store soil moisture in degraded pasture have effects on the reduction of transpiration. In addition, over pastureland, less precipitation is intercepted and re-evaporated when the roughness length is relatively smaller, thus affecting evapotranspiration and air temperature. These results show that the increase in GHGs and the inclusion of deforestation contribute to changes in the energy and radiation budgets, and these changes become more intense as the degree of deforestation in the Amazon basin also increases.

3.2. Changes in precipitation and moisture convergence

The changes in precipitation, moisture transport and convergence projected by the Eta-BESM-OA simulations are shown in Figs. 5 & 6. In the baseline period, the pattern of atmospheric circulation over the continent during the rainy season shows intense moisture transport and convergence in the Amazon basin and in central Brazil. In the dry season, this regime is weakened, favoring a moisture convergence pattern positioned to the north of South America and, thus, configuring a seasonal regime of monsoon in South America (Gan et al. 2004). The Eta-BESM-OA model was able to represent the seasonal and spatial variation in the moisture transport and convergence, presenting positive values (convergence) on the Amazon basin and negative (divergence) in northeast Brazil (Fig. 6a,e). Under the RCP8.5 scenario, there are significant changes in the moisture convergence over the Amazon basin, with a 25% reduction during the wet season, thus affecting moisture transport and precipitation over the region. The reduction in precipitation in the wet season occurs in an area that extends from the Amazon basin (3.5 mm d^{-1}) and passes through the central regions and on to southern Brazil (2.5 mm d^{-1}), regions where the Southern Atlantic Convergence Zone is located. The precipitation in the region of the ITCZ appeared weak and moved to the north of its climatological position in the tropical Atlantic, thus producing less rain in the Amazon basin. The changes in precipitation in the dry season showed a reduction pattern in the north and an increase in the south of the basin, which extended to central-southern Brazil. In contrast with the present study, Guimberteau et al. (2017) observed a tendency of an average increase in precipitation over the basin at the end of the 21st century. Marengo et al. (2012) found a marked reduction in precipitation in most of the Amazon basin towards the end of the 21st century when assessing climate changes using projections by the Eta model driven by the global HadCM3 model under the SRES A1B scenario. When including deforestation scenarios in South America, these results show intensification in the changes, and expansion of the affected area, mainly in the Amazon basin.

These results show that the changes under the RCP8.5-only scenario and under deforestation scenarios can affect the thermodynamic structure of the atmosphere and consequently the regional circulation, which produces impacts that extend beyond the limits of deforestation (Fig. 6c,d).

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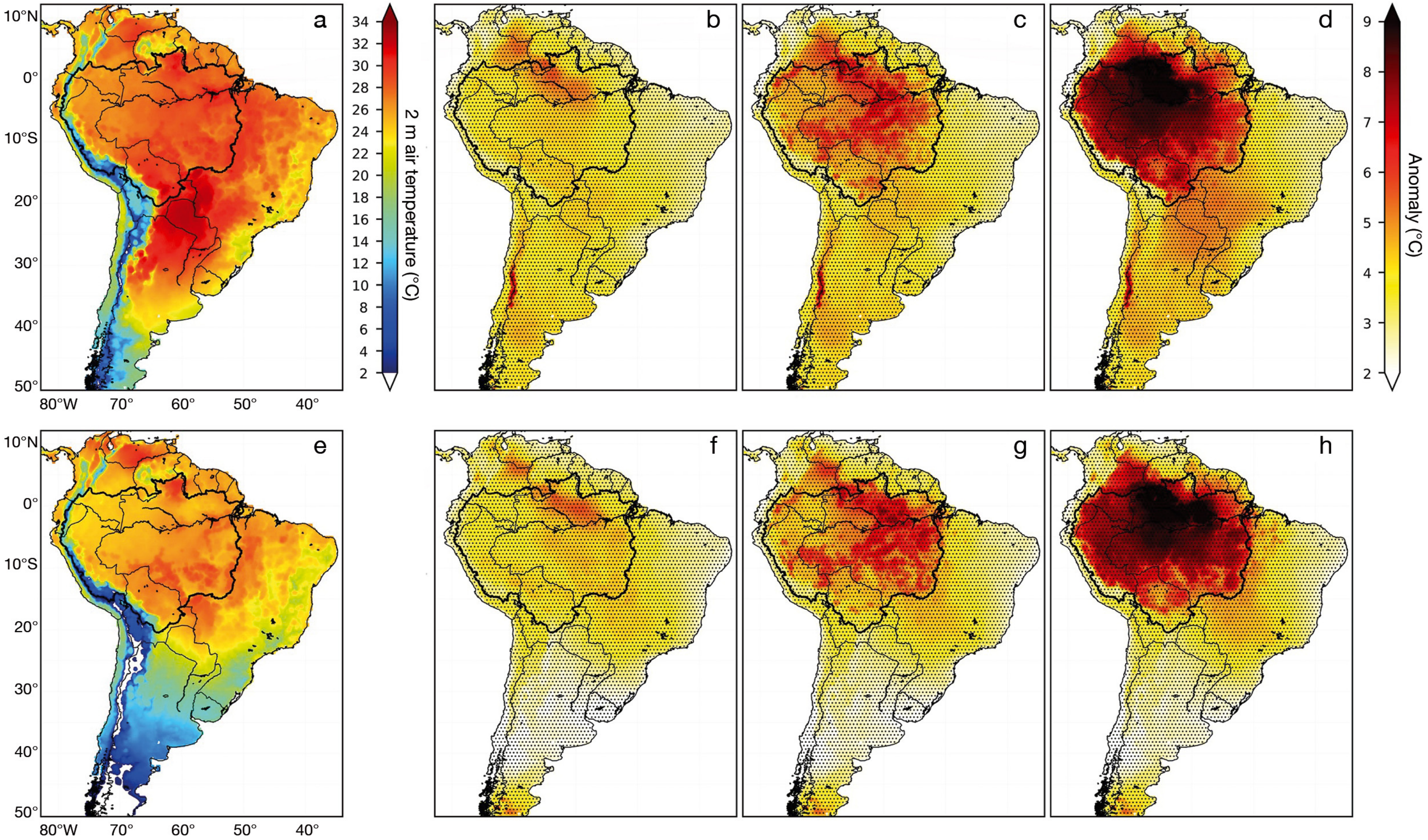

Fig. 3. Effects on air temperature at 2 m (°C) from land use changes and emission scenario (RCP 8.5) for wet and dry seasons. Wet season: (a) Air temperature for the baseline period. Impacts on air temperature: (b) RCP8.5 scenario and 2015 vegetation, (c) RCP8.5 and 2050 deforestation scenario, (d) RCP8.5 and 2100 deforestation scenario, both relative to the baseline period. Dry season: (e) air temperature for the baseline period. Impacts on air temperature: (f) RCP8.5 scenario and 2015 vegetation, (g) RCP8.5 and 2050 deforestation scenario, (h) RCP8.5 and 2100 deforestation scenario, both relative to the baseline period. Areas where differences are significant at the 95% confidence level are marked by black dots

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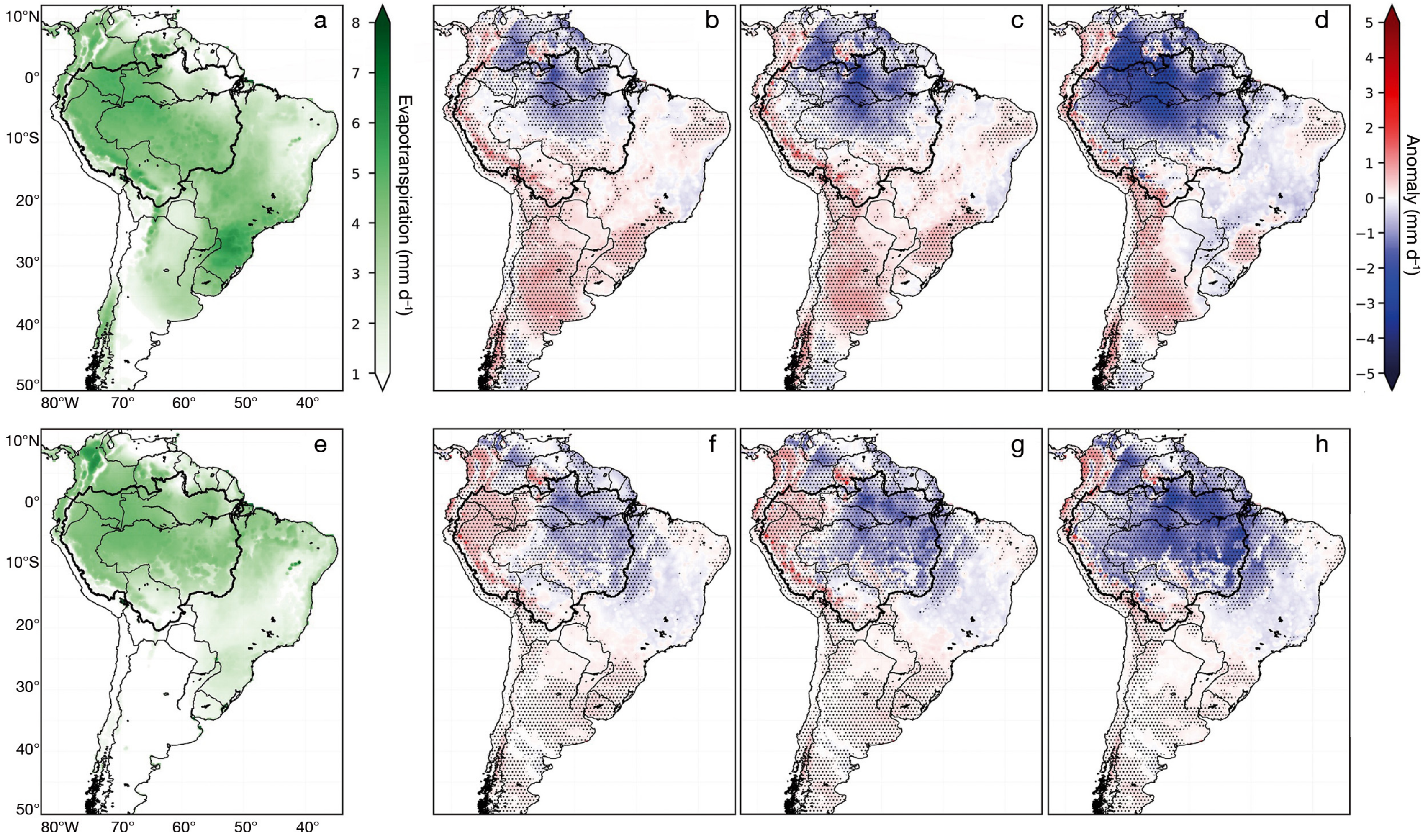

Fig. 4. Effects on evapotranspiration (mm d^{-1}) from land use changes and emission scenario (RCP 8.5) for wet and dry seasons. Other details as in Fig. 3

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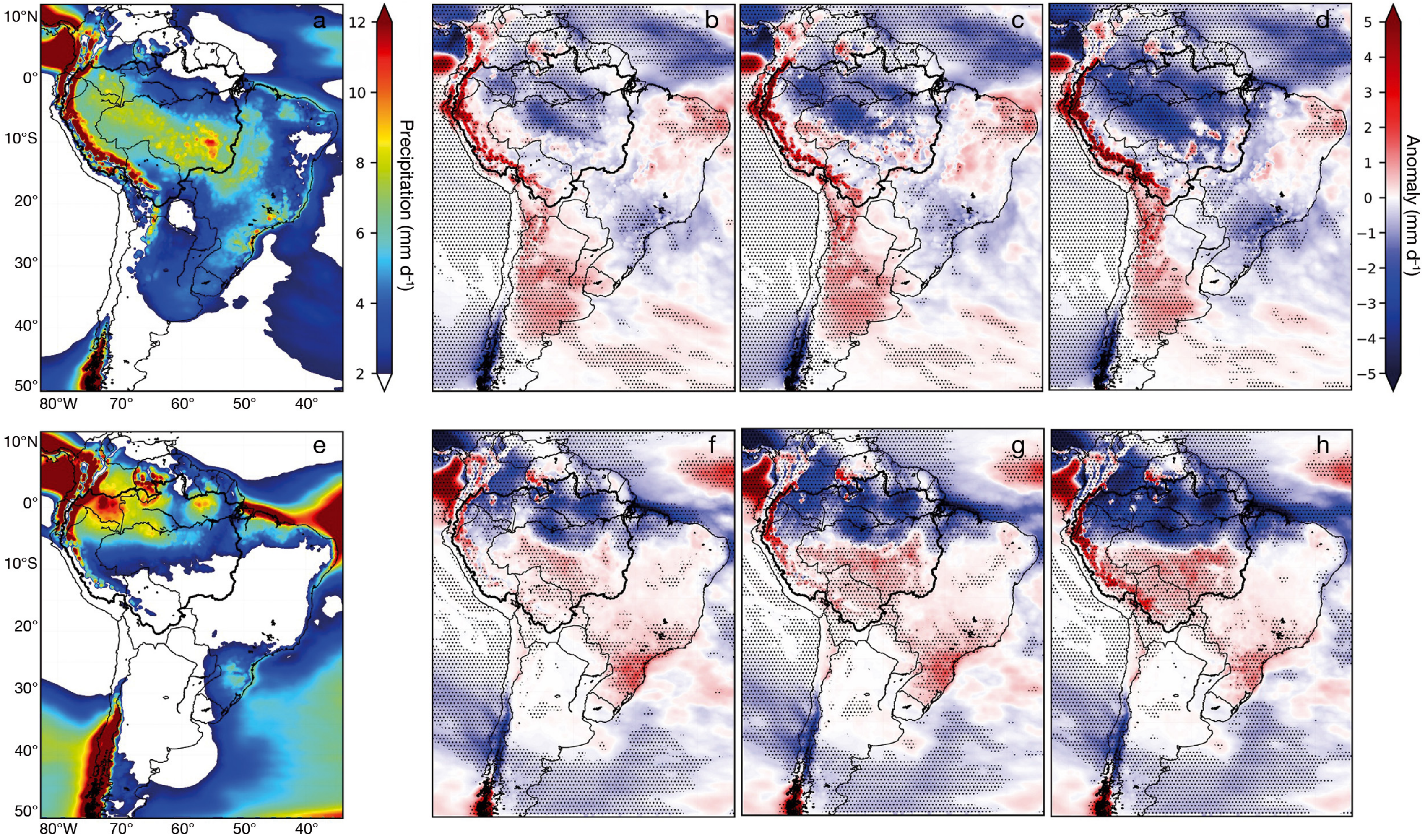

Fig. 5. Effects on precipitation (mm d^{-1}) from land use changes and emission scenario (RCP 8.5) for wet and dry seasons. Other details as in Fig. 3

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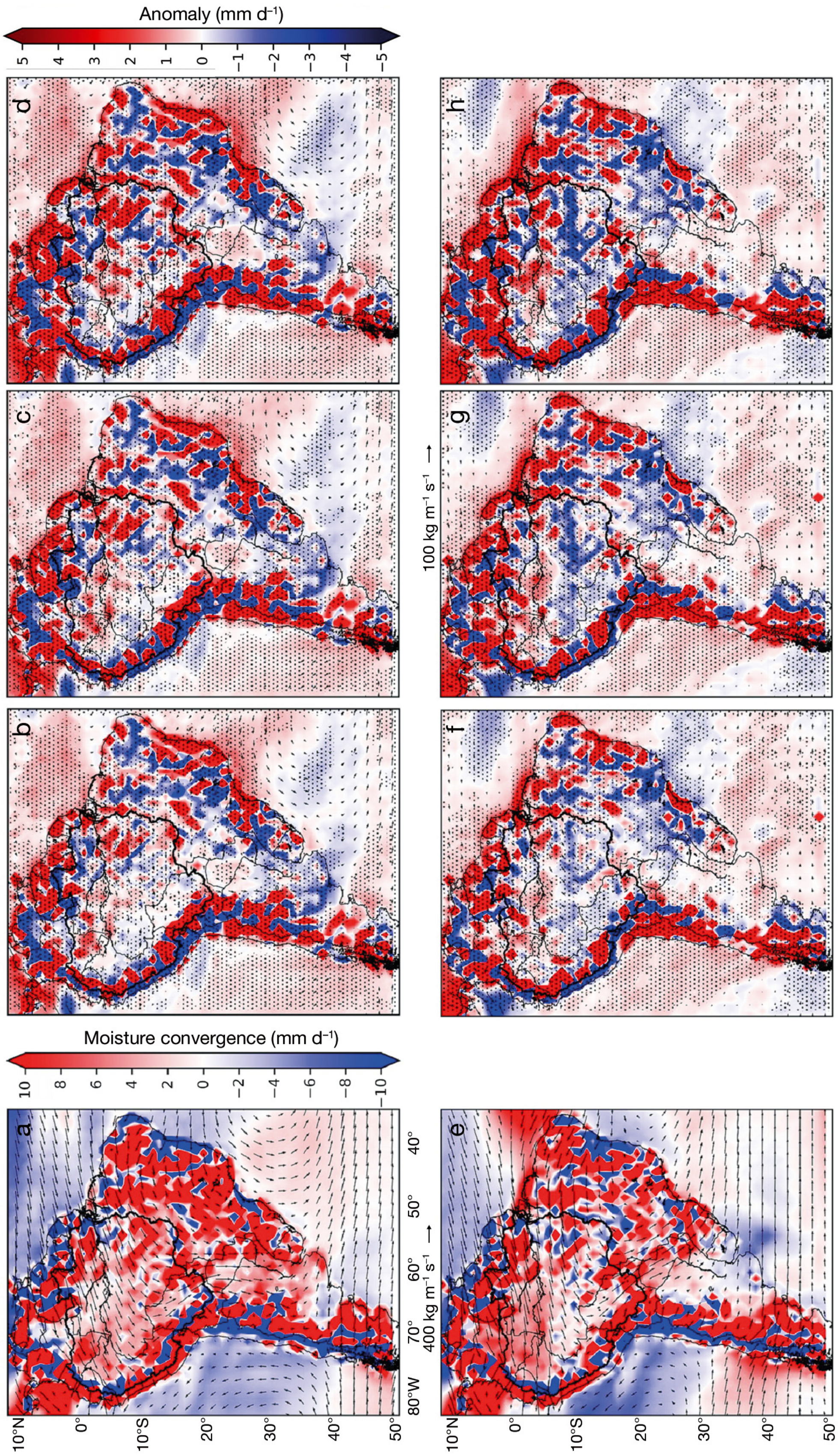

Fig. 6. Effects on the moisture convergence (mm d^{-1}) from land use changes and emission scenario (RCP 8.5) for wet and dry seasons. Other details as in Fig. 3

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The inclusion of the 2050 (2100) deforestation scenarios during the wet season (dry season) caused substantial reduction in rainfall of −1.2 mm d^{-1} (−1.7 mm d^{-1}). During the dry season, a reduction in rainfall is projected in the northern basin and an increase is projected in the southern basin, where the deforestation arc is located (Costa & Pires 2010).

Under the RCP8.5 scenario, the reduction in precipitation is determined by the reduction in evapotranspiration and moisture convergence, mainly by the latter. On the other hand, with the inclusion of the 2050 and 2100 deforestation scenarios, the reduction in evapotranspiration played a predominant role (Figs. 5 & 6).

3.3. Changes in the water budget

Fig. 7 shows the annual cycle of the components of the water budget, i.e. rainfall, evapotranspiration and moisture convergence, in the entire Amazon basin and in the northern and southern basins separately. The features of the monsoon regime in South America and the north–south shift of the ITCZ are shown by the seasonal variability of the water budget in the southern portion in comparison with the northern portion of the basin. The seasonal cycle of simulated precipitation in this study was similar to that found by Chou et al. (2014a), where the performance of the regional Eta model forced by 3 global climate models (HadGEM2-ES, BESM and MIROC5) was evaluated for the baseline period.

Under the RCP8.5 scenario, the reduction in precipitation was more marked in the center-southern portion of the basin and during the rainy season, with a reduction on the order of 10%. This reduction in precipitation was clearly caused by the reduction in moisture convergence (11%), since evapotranspiration showed little variation in this season (Fig. 7, see also Table 2). Under the 2050 and 2100 deforestation scenarios, rainfall reductions are projected for the wet season in the central-southern part of the Amazon basin of about 13 and 23%, respectively. The reductions in moisture convergence which determined these changes in precipitation were 10 and 18% for the 2050 and 2100 scenarios, respectively.

On the other hand, during the dry season, despite the substantial reduction in the evapotranspiration (24% for 2050 and 33% for 2100 deforestation scenarios), the precipitation component shows some increase due to the increase in the moisture convergence. The precipitation and evapotranspiration reductions in the deforestation scenarios during the rainy season acted to amplify the soil moisture stress, altering the energy partitioning and, consequently, the surface temperature (Fig. 3).

The projected changes in the water budget components with respect to the reference period (1979–2005) for the Amazon basin are shown in Table 2. In the basin, precipitation simulated by Eta-BESM-OA is always larger than evapotranspiration, which identifies the region as a moisture sink area, and shows that the regional model was able to capture this characteristic feature of the Amazon basin. This sinking feature also occurs either in neutral conditions or in climatic extremes such as during El Niño and La Niña episodes (Marengo 2005). Under the additional deforestation scenarios, the impacts on the water cycle are intensified over the entire basin. Under the RCP8.5-only scenario, the model simulated reductions of 11% in precipitation, 6% in evapotranspiration, 9% in moisture convergence and 34% in runoff in the annual average. Fig. 8 presents conceptual diagrams of positive and negative feedbacks associated with increases in carbon dioxide and land use. The positive feedback mechanism can lead to instability in the natural ecosystems of the Amazon, since they do not have a sufficient capacity to adapt to changes in climate, especially if they occur over a short time (decades). With the deforestation scenarios for 2050 and 2100, a 13 and 19% reduction in precipitation and a 12 and 20% reduction in evapotranspiration were projected, respectively. However, for the annual average in the basin, there is a small increase in the convergence of humidity in the scenarios of 2050 and 2100. Unlike the RCP8.5 scenario and the 2015 vegetation map, the negative feedback mechanism was predominant with the inclusion of deforestation, in which the relative reduction in evapotranspiration was greater than the reduction in precipitation, leading to an increase in the convergence of moisture on the region (Fig. 8b). Despite the changes in the regional circulation, and consequently in the transport and convergence of humidity, the effects of the reduction in evapotranspiration in the deforestation scenarios were more significant for the reduction of precipitation towards the end of the 21st century in the Amazon basin.

4. CONCLUSIONS

In the present study, the Eta regional model, driven by the BESM-OA model, was used to generate simulations of climate change from the RCP8.5 scenario and of future deforestation in the Amazon basin. The

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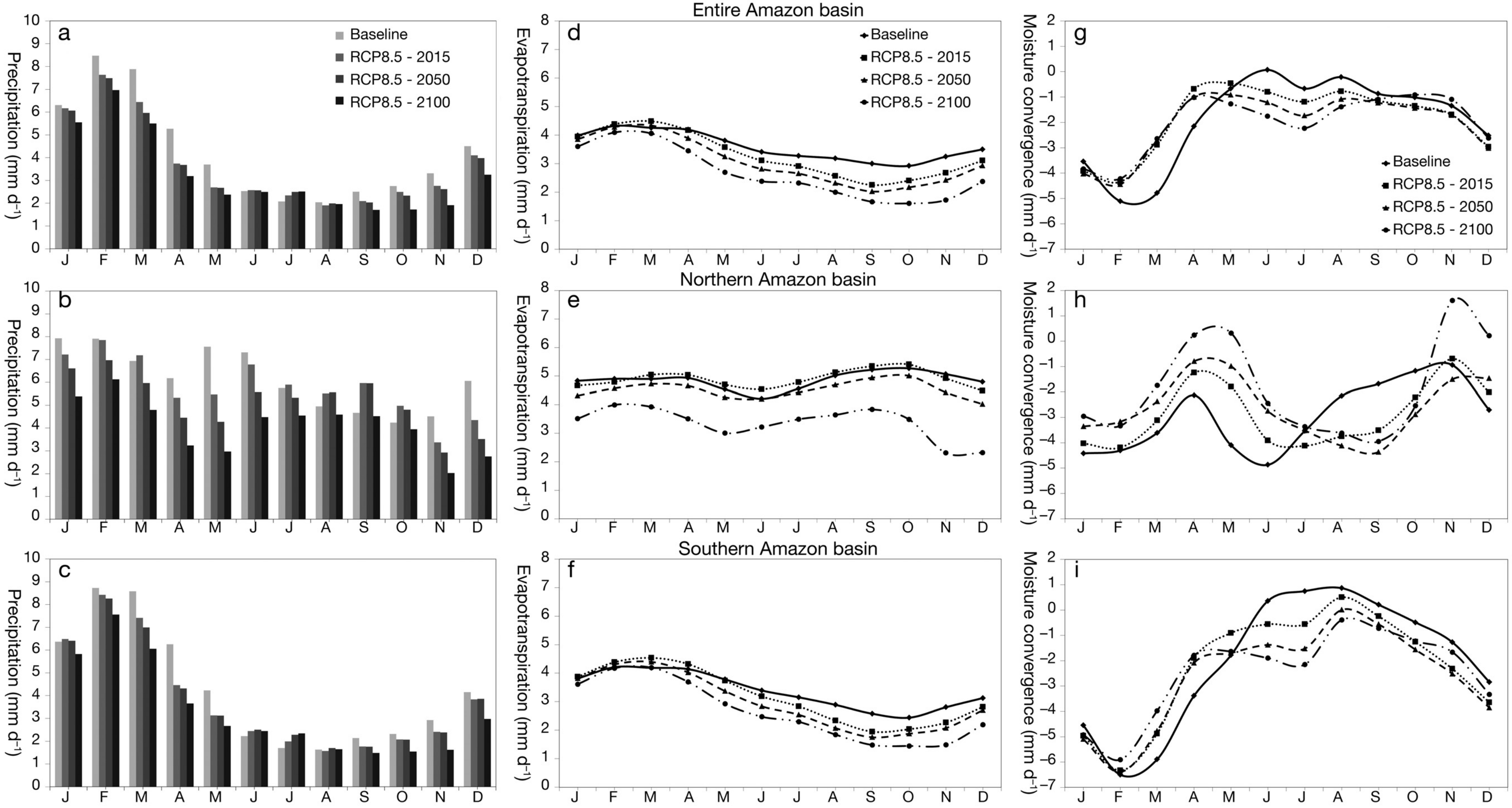

Fig. 7. Seasonal variability in the components of the water budget simulated by the Eta-BESM-OA model for the present climate (1979–2005) and the future period (2071–2100) using the RCP 8.5 emission and deforestation scenarios for 2015, 2050 and 2100 (mm d^{-1}), for the entire Amazon basin, the northern Amazon basin and the southern Amazon basin. (a,b,c) Precipitation, (d,e,f) evapotranspiration and (g,h,i) moisture convergence

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Table 2. Mean annual changes and linear trends of the water budget components. TP2m: air temperature at 2 m (°C); PRE: precipitation (mm d^{-1}); EVT: evapotranspiration (mm d^{-1}), MOC: moisture convergence (mm d^{-1}); RUN: surface runoff (mm d^{-1}) for RCP 8.5 emission and land use scenarios (2015, 2050 and 2100), in relation to baseline period. The linear trends are also included, and changes are shown for annual means. Data are provided for the entire Amazon basin, as well as the northern and southern Amazon basins separately

Region	Change (%)					
	2015	Trend	2050	Trend	2100	Trend
Entire basin						
TP2m	4.1	0.0107	5.0	0.0129	6.4	0.0159
PRE	−11.3	−0.0015	−12.9	−0.0017	−19.4	−0.0024
EVT	−6.1	−0.0008	−11.6	−0.0013	−20.4	−0.0024
MOC	−9.5	−0.0002	0.1	0.0006	4.3	0.0007
RUN	−34.3	−0.0007	−58.9	−0.0004	−57.6	−0.0003
Northern basin						
TP2m	4.0	0.0098	4.8	0.0117	8.5	0.0198
PRE	0.2	−0.0009	−10.1	−0.0025	−27.0	−0.0046
EVT	2.0	0.0009	−5.3	−0.0009	−24.5	−0.0033
MOC	4.3	0.0005	−8.5	−0.0015	−20.8	−0.0029
RUN	−5.1	−0.0010	−24.5	−0.0016	−34.5	−0.0012
Southern basin						
TP2m	3.9	0.0102	4.8	0.0124	5.9	0.0146
PRE	−8.1	−0.0013	−9.0	−0.0014	−17.5	−0.0023
EVT	−3.3	−0.0006	−9.2	−0.001	−16.2	−0.0017
MOC	−11.4	−0.0002	−3.2	−0.0009	−3.4	−0.0009
RUN	−22.9	−0.0008	−8.3	−0.0004	−21.7	−0.0006

simulations of the baseline period reproduced the moisture sink characteristics, and revealed a precipitation rate higher than the evapotranspiration rate in the basin. Under the RCP8.5-only scenario, Eta-BESM-OA projections showed climate change over all of South America, and indicated a more significant increase over the central and northern portions of the Amazon basin (4–5°C). In the RCP8.5 emission scenario and the vegetation map of 2015 by the end of the 21st century, the positive feedback mechanism predominated, in which the reduction in evapotranspiration and moisture convergence acted in the same direction to reduce precipitation over the Amazon basin. Changes in temperature and water budget components were intensified with the inclusion of future deforestation, which showed that the increase in GHGs and changes in land use contribute synergistically to affect the energy and water budget over the Amazon basin. With the deforestation

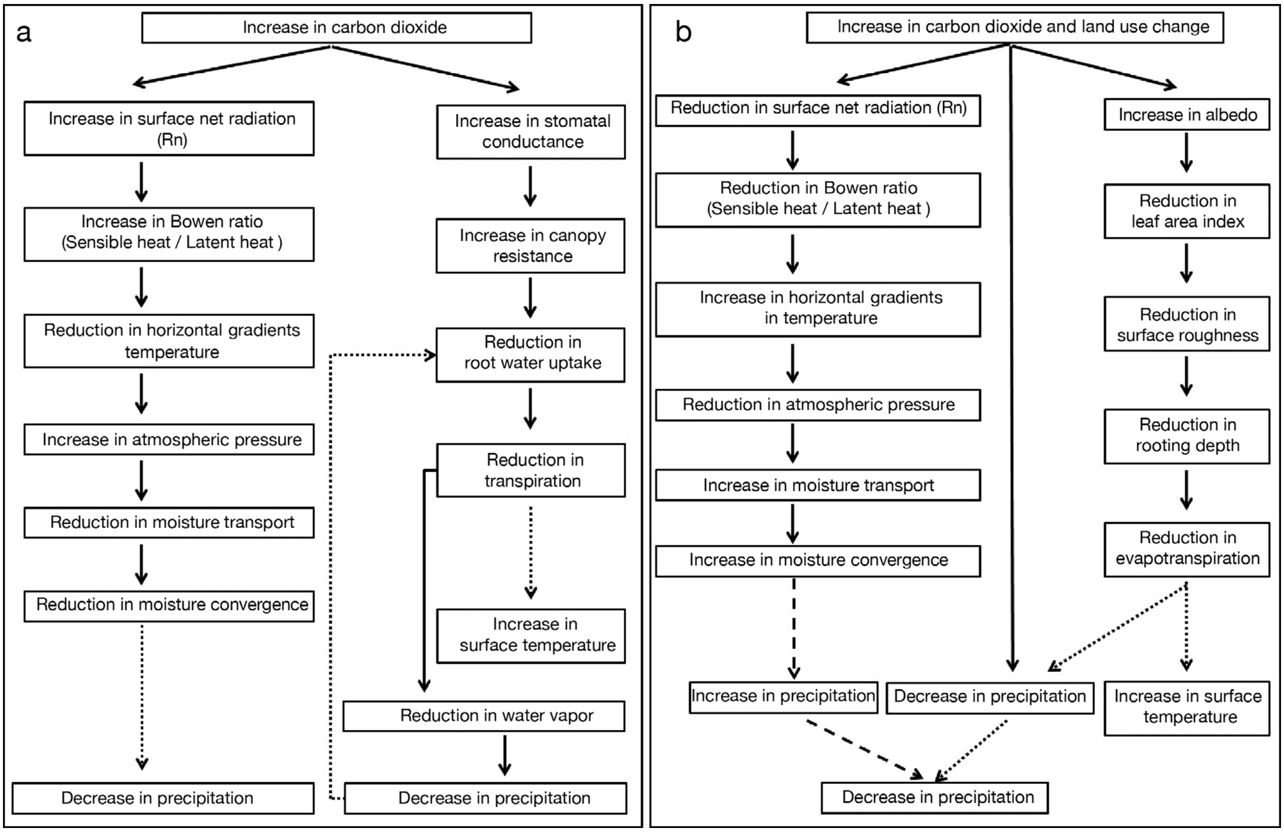

Fig. 8. Conceptual diagram summarizing the impacts of (a) increases in carbon dioxide and (b) increases in carbon dioxide and land use change. Arrows — solid: processes of atmosphere biosphere interactions; dotted: positive feedback; dashed: negative feedback

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scenarios, the negative feedback mechanism was predominant, in which the relative reduction in evapotranspiration was greater than the reduction in precipitation; this led to an increase in the convergence of moisture over the region. The changes in the water budget in the Amazon due to anthropogenic factors are a worrying scenario. These changes may trigger significant changes in the natural ecosystems of the Amazon, since these ecosystems do not possess a sufficient capacity to adapt to the magnitude of the changes in the climate, especially if they occur in a short timeframe. The results obtained in this study emphasize the need for public conservation policies to halt the increase in environmental degradation in the Amazon basin and to reduce GHG emissions caused by the burning of fossil fuels.

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