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Talamoni, I.L., Kubota, P.Y., Cavalcanti, I.F.A. et al. (2024) Numerical assessment of changes in land–atmosphere interactions during the rainy season in South America using an updated vegetation map. *International Journal of Climatology*, 44 (10). pp. 3278-3294. ISSN: 0899-8418

<https://doi.org/10.1002/joc.8523>

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**NUMERICAL ASSESSMENT OF CHANGES IN LAND-ATMOSPHERE
INTERACTIONS DURING THE RAINY SEASON IN SOUTH AMERICA
USING AN UPDATED VEGETATION MAP**

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Keywords: **Rainy Season**; Land Use and Land Cover Change; Atlantic Forest; IBIS; BAM.

Funding: *Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - CAPES* (process 88887.354679/2019-00) associated with CLIMAX-FAPESP-Belmont-2015/50687-8 and CNPq – Project 306393/2018-2.

Abstract

Land Use and Land Cover Change (LULCC) is a key driver of changes in land-atmosphere interactions, playing an essential role in climate and weather patterns in South America (SA). This study used a modelling approach to assess the land-atmosphere changes introduced by LULCC over the Brazilian territory. Numerical experiments of early (2006), neutral (2004), and late (2008) rainy season onset years were performed in the Integrated Biosphere Simulator (IBIS) to assess the land-surface parameters, and in Brazilian Atmospheric Model (BAM) to assess the atmospheric variables. The models were run with a natural (NAT) vegetation map and an updated (UP) vegetation map, which incorporated realistic Brazil deforestation up to the early 2000s. The differences between the two maps were particularly larger over 25-15°S and 50-40°W, where the Atlantic Forest and Cerrado biomes were replaced by pasture. IBIS experiments showed that over the area of larger LULCC there was an increase in albedo of up to 8% while reductions in net radiation, surface heat fluxes, surface temperature, and surface roughness were noticed. Land-atmosphere feedbacks assessed with BAM experiments showed that LULCC contributed to a drier and colder (stable) atmosphere over central-east SA that opposes the necessary conditions for the rainy season onset. The changes included increases in surface pressure and low-level wind associated with reductions in 2 m temperature and surface roughness. These changes contributed to decrease the cloud formation and less precipitation in all three rainy season onset years, but particularly in the late rainy season onset year during September-October-November (SON). The atmospheric changes induced by LULCC show a pattern of dry atmosphere (reduced precipitation), similar to those of late onset years, and indicate that LULCC enhances the late rainy season onset condition over central-east SA. Additionally, this study highlights the importance of considering up-to-date vegetation maps because these changes significantly affect both surface and atmospheric variables.

Keywords: Rainy Season; Land Use and Land Cover Change; Atlantic Forest; IBIS; BAM.

29 **1. Introduction**

30 The South American Monsoon System (SAMS; Zhou and Lau, 1998; Gan et al.,
31 2004; Vera et al., 2006; Marengo et al., 2012; De Carvalho and Jones, 2016) is a
32 prominent seasonal variability mode comprising all the central and east areas of South
33 America (SA). It is characterized by well-defined annual dry and rainy seasons (Gan et
34 al., 2004). SAMS seasonal variability is often verified through the reversal of the low-
35 level circulation monthly anomalies (wind annual mean remotion), and through the
36 seasonal shift in precipitation and Outgoing Longwave Radiation (OLR) over SA (Zhou
37 and Lau, 1998, Gan et al., 2004). Although SAMS is one of the main contributors to the
38 rainy season in SA, herein we consider the rainy season as the period when persistent
39 precipitation is established over the central and east areas of SA (Liebmann and Marengo,
40 2001; Bombardi et al., 2019).

41 Different methodologies were developed to identify the rainy season onset, but
42 they all converge to the onset between mid-October and mid-November over the SA
43 northwest region, gradually extending southeastward and reaching the precipitation peak
44 between December and February (Kousky, 1988; Liebmann and Marengo, 2001; Gan et
45 al., 2004; Silva and Carvalho, 2007; Raia and Cavalcanti, 2008; Nieto-Ferreira and
46 Rickenbach, 2011).

47 Local forcings, such as Land Use and Land Cover Change (LULCC), contribute
48 to the SA rainy season. Modeling studies have shown that circulation and precipitation
49 variabilities in particular SA rainy season regions, such as the southern Amazon, are
50 primarily influenced by local factors rather than remote ones (Marengo et al., 2003; Fu
51 and Li, 2004; Xue et al., 2006; Ma et al., 2011). Additionally, the evaporation at the end
52 of the dry season over the Amazon region has been pointed out as triggering mechanism
53 to SAMS onset (Li and Fu, 2004). Therefore, land-atmosphere interactions are a local
54 forcing that plays an important role in climate and weather of SA (Collini et al., 2008; Da
55 Rocha et al., 2009; Souza, 2009; Aragão, 2012; Khanna et al., 2017). LULCC has become
56 a prominent study subject due to its direct impact on both local and regional climates
57 (e.g., Yang and Dominguez et al., 2019). Studies have established a link between
58 deforestation and the rainy season onset delay in the southern Amazon (Butt et al., 2011;
59 Debortoli et al., 2015; Leite-Filho et al., 2019). Chambers and Artaxo (2017) attributed
60 the delay in rainy season onset to changes in surface roughness. Furthermore,
61 deforestation has been linked to reduced precipitation due to evapotranspiration and

62 moisture transport decrease (Spracklen and Garcia-Carreras, 2015; Spracklen et al.,
63 2018), as well as temperature increase over the southern Amazon (Rezende et al., 2022).
64 Wright et al. (2017) identified an important mechanism involving the link between the
65 Amazon Forest transpiration and the increase in shallow convection during the dry to
66 rainy-season transition. This moisture pumping through shallow convection is considered
67 a precondition to the rainy season onset. These studies motivate the hypothesis explored
68 in our present study that LULCC affects the rainy season in SA.

69 LULCC presents a major threat to natural biomes. In 2021, only 12.4 % of the
70 original Atlantic Forest (Southeast and south of Northeast regions of Brazil) was still
71 preserved (SOS Mata Atlantica, 2021). Since LULCC modifies land-atmosphere
72 interactions, it is essential to provide realistic and up-to-date vegetation maps in both
73 land-surface and Atmospheric General Circulation Models (AGCM) to ensure accurate
74 simulations (Cavalcanti et al., 2017). In the present study, an offline framework with the
75 Integrated Biosphere Simulator (IBIS; Kubota, 2012) was used to assess the land-surface
76 parameters, while an online framework with the Brazilian Atmospheric Model (BAM;
77 Figueroa et al., 2016; Lima, 2021) was used to assess the atmospheric **variables**. These
78 frameworks were employed to investigate how LULCC affects the surface and
79 atmospheric **variables** during the SA rainy season. An updated vegetation map was
80 implemented into IBIS and BAM to assess, respectively, the surface and atmospheric
81 sensitivity to LULCC. These numerical modelling experiments provide insights into how
82 LULCC affects the SA rainy season and what is the importance of considering LULCC
83 in AGCMs. The updated vegetation map included LULCC over the Brazilian territory
84 with historical deforestation that occurred up until the early 2000s, particularly the
85 replacement of the Atlantic Forest and Cerrado.

86 **2. Data and Methods**

87 **2.1 Data**

88 Table I provides a detailed overview of the data utilized in this study. The initial
89 condition of IBIS-OFFLINE experiments was data from the Global Land Data
90 Assimilation System which is a rain gauge and satellite-based dataset (GLDAS;
91 Beaudoin and Rodell, 2020). ERA5 reanalysis hourly data (Hersbach et al., 2023) was
92 used as the initial condition for BAM 3D experiments. The boundary condition over the
93 oceans in BAM 3D experiments was from the NCEP – NOAA sea surface temperature

94 data (Huang et al., 2020). Additionally, the initial soil water content conditions were
95 derived from GLDAS.

96 **2.2 Rainy season onset years selection**

97 Talamoni et al. (2022) developed a methodology using the Rainy And Dry Season
98 (RADS; Bombardi et al., 2019) global dataset to identify years marked by early and late
99 rainy season onsets in SA. The authors, calculated onset date anomalies using RADS and
100 classified years as early (late) onset based on whether the percentage of negative
101 (positive) onset date anomalies in central SA exceeded 60% (Talamoni et al., 2022).
102 Neutral rainy season onset was determined by a nearly 50% percentage in central SA.
103 Based on these selection criteria, 2006 (September 30), 2004 (October 11), and 2008
104 (November 11) were selected as representative years for early, neutral, and late rainy
105 season onsets, respectively. More details of early, neutral, and late onset years can be
106 found in Talamoni et al. (2022). Figure 1 shows ERA5 variables (sea level pressure,
107 moisture flux and wind at 850 hPa) and GPCP precipitation differences between the early
108 and late onset years in the months of SON (September-October-November) and DJF
109 (December-January-February). During SON and DJF, precipitation was greater over the
110 northwest (central-east) SA in the late (early) onset year (Figure 1d, h). In SON, negative
111 SLP differences were observed over Argentina and center-west of South Atlantic Ocean
112 (Figure 1a) which indicates higher SLP in the late onset. Talamoni et al. (2022)
113 investigated the development of a high SLP system in late onset years which was
114 associated with atmospheric blocking episodes contributing to a delay in the rainy season
115 onset. In DJF, negative SLP differences extended from the south Pacific to South Atlantic
116 southward of 35°S (Figure 1e), indicating a predominance of lower pressure systems in
117 extratropical latitudes in the early onset year compared to the late onset year, which may
118 have played a role in the development of transient weather systems. During DJF, these
119 systems acquire a stationary behavior that contributes to organizing the northwest-
120 southeast precipitation band over SA called the South Atlantic Convergence Zone
121 (SACZ; Kodama, 1992), which also explains the precipitation anomalies over the central-
122 east SA in the early onset year (Figure 1h). SACZ is the main convective feature
123 associated with SAMS. Its features can be identified by the northwesterly moisture flux
124 that extends from the Amazon Basin towards the Southeast region of Brazil and the
125 Atlantic Ocean. Figure 1f shows the enhanced moisture flux over central-east SA in the

126 early onset year. This enhanced moisture flux is accompanied by enhanced 850-hPa wind
127 speed across central SA (Figure 1g) meaning that more moisture is advected by the
128 northwesterly flux. The **intensity** of the differences in Figure 1 is **relatively high compared**
129 **to climatology**, in particular for precipitation and moisture flux.

130 **2.3 Vegetation Maps**

131 The two vegetation maps used in the numerical experiments for IBIS and BAM
132 models are shown in Figure 2. The natural vegetation map (NAT) in Figure 2a uses IBIS
133 vegetation classes (Foley et al., 1996) and has a spatial resolution of $0.5^{\circ} \times 0.5^{\circ}$. NAT
134 vegetation map is implemented in the Brazilian Atmospheric Model (BAM; Figueroa et
135 al., 2016).

136 Figure 2b shows the Brazilian ProVeg map, an updated representation of
137 vegetation cover and land use for the Brazilian territory derived from the ProVeg project
138 (Vieira et al., 2013). This map is a result of satellite data and remote sensing techniques
139 combined with geographic datasets and deforestation data from Environmental Programs
140 such as PRODES and SOS *Mata Atlântica* for the early 2000s. The ProVeg project map
141 has a spatial resolution of 1 km ($0.01^{\circ} \times 0.01^{\circ}$) (Vieira et al., 2013) and uses the SSiB
142 vegetation scheme classes (Xue et al., 1991).

143 The updated vegetation map (UP) in Figure 2c was obtained from the merge
144 between the Brazilian land cover map from the ProVeg project in Figure 2b and the NAT
145 map in Figure 2a. To merge NAT and ProVeg vegetation maps, an algorithm to establish
146 the relationship between the IBIS and SSiB vegetation classes was used. The relationship
147 between these two model's vegetation classes is shown in Figure 2d. UP vegetation map
148 has a spatial resolution of $0.5^{\circ} \times 0.5^{\circ}$ and uses IBIS vegetation scheme classes. The main
149 differences between NAT and UP vegetation maps were particularly evident in the
150 Atlantic Forest (Southeast and south of Northeast regions of Brazil) and the Cerrado
151 (Northeast and Central-East regions of Brazil) biomes that were replaced by pasture in
152 the UP vegetation map (Figure 2c).

153 **2.4 IBIS-OFFLINE experiments**

154 Global numerical experiments were performed using the land-surface model IBIS
155 version Agro-IBIS 2.6b5 implemented by Kubota (2012). IBIS experiments were offline
156 meaning that dynamic vegetation feedback from the land to the atmosphere was not

157 assessed in this study. This approach is consistent with previous research conducted by
158 Rezende et al. (2022) and Ruscica et al. (2022).

159 The vegetation parameters were obtained from model calibration studies with in-
160 situ data (Imbuzeiro, 2005; Senna et al., 2009; Cunha et al., 2013; Araújo et al., 2016).
161 For each rainy season onset year (early, neutral and late), two experiments were
162 performed: one with the NAT vegetation map (Figure 2a) and the other with the UP
163 vegetation map (Figure 2c). In total, six numerical experiments were performed over the
164 simulation period from 1 July to 28 February of each respective rainy season onset year
165 (Table 2). IBIS model was configured to a Gaussian grid resolution with triangular
166 truncation of 126 waves (approximately $1^\circ \times 1^\circ$ of horizontal resolution).

167 **2.5 BAM 3D experiments**

168 AGCM experiments were performed to assess the land-atmosphere feedback due
169 to LULCC. The AGCM used to perform the numerical experiments was the Brazilian
170 Atmospheric Model (BAM; Figueroa et al., 2016) version 2.2.1 (Lima, 2021). BAM is a
171 spectral model with hybrid vertical coordinates. Its dynamical core is a monotonic two-
172 time-level semi-Lagrangian scheme, i.e., the tridimensional transport of moisture,
173 microphysical (liquid water, ice, etc), and tracer prognostic variables (ozone, carbon
174 dioxide) are solved at each grid point. BAM has $\sim 1^\circ \times 1^\circ$ of horizontal resolution, i.e.,
175 triangular quadratic truncation with 126 waves and 42 vertical levels (from 1000 to 2 mb).
176 Detailed configurations of the model's physical processes are in Table 3.

177 Table 4 shows the five experiments performed for each rainy season onset
178 condition (early, neutral and late). The experiment's initial condition date varied from the
179 first to the fifth day of the month, therefore, ensemble analyses were performed. Each
180 experiment was performed for both vegetation maps, NAT and UP, thus, a total of ten
181 experiments were obtained for each rainy season onset condition and for each simulation
182 period (one from July to March and the other from October to May). The simulation
183 period was split into two to guarantee a closer soil moisture initial condition from
184 GLDAS. It ensures that the DJF simulation has a less dry moisture initial condition in
185 October compared to the one in July. Thus, the July to March (October to May) simulation
186 period was used for SON (DJF) analysis. DJF analysis was included due to differences
187 between early and late rainy season onset years identified in Figure 1h and also by

188 Talamoni et al. (2022). Therefore, DJF analysis is relevant to assess if different rainy
 189 season onset dates can affect the rainy season period and its associated features.

190 2.6 t-Student test

191 Student's t statistical test (Spiegel, 1979) at a significance level of 5% was used
 192 to assess the differences between BAM 3D experiments with NAT and UP vegetation
 193 maps. The null hypothesis considered in the test was that changes in atmospheric
 194 variables were not related to LULCC. The critical value (t) was obtained from a two-
 195 tailed table with 8 degrees of freedom ($N_{NAT} + N_{UP} - 2$). N_{NAT} and N_{UP} are the sample
 196 size, i.e., the number of BAM 3D experiments performed with each vegetation map ($N =$
 197 $N_{NAT} = N_{UP} = 5$). μ_{NAT} and μ_{UP} are the NAT and UP experiments ensemble averages,
 198 respectively. s_{NAT} and s_{UP} are the standard deviation expressed by equation 3. The
 199 covariance coefficient (σ) was obtained by equation 2, and subsequently, the t-value (t)
 200 was determined by equation 1.

$$\left\{ \begin{array}{l}
 t = \frac{\mu_{NAT} - \mu_{UP}}{\sigma \sqrt{\frac{1}{N_{NAT}} + \frac{1}{N_{UP}}}} \quad (1) \\
 \sigma = \sqrt{\frac{N_{NAT} \cdot s_{NAT}^2 + N_{UP} \cdot s_{UP}^2}{N_{NAT} + N_{UP} - 2}} \quad (2) \\
 s = \sqrt{\frac{\sum (X_i - \mu)^2}{N - 1}} \quad (3)
 \end{array} \right.$$

202 2.7 Water Budget

203 A surface water budget analysis was performed, similar to Talamoni et al. (2022). The
 204 objective was to differentiate the contribution of each water budget component in UP and
 205 NAT experiments. The water budget (WB) components shown in equation 4 are: the total
 206 vertically integrated water vapour flux divergence over the rectangular area (C_w),
 207 precipitation (P), evapotranspiration (E) and runoff (R). The rectangular area is the area
 208 between 25-15°S and 50-40°W. P is the total precipitation ($\text{kg m}^{-2} \text{ day}^{-1}$) and R is the
 209 runoff ($\text{kg m}^{-2} \text{ day}^{-1}$), both output variables from BAM. Likewise, the latent heat flux
 210 (LE) from surface (W m^{-2}) is an output from BAM. LE was converted to E as equation 5
 211 (Allen et al., 1998) where λ is the latent heat of vaporization at 25°C °C ($2.4 \times 10^6 \text{ J kg}^{-1}$).
 212 E was converted from $\text{kg m}^{-2} \text{ s}^{-1}$ to mm day^{-1} .

213 To compute C_w , shown in equation 8, we employed box model calculations (Satyamurty
 214 et al., 2013) which is the sum of the vertically integrated water vapour flux divergence
 215 across the four walls over the area between 25-15°S and 50-40°W. T_e , T_w , T_s and T_n are
 216 the water vapour transport across the eastern, western, southern and northern walls,
 217 respectively. C_w is in units of $\text{kg m}^{-2} \text{s}^{-1}$, later converted to mm day^{-1} . It is also noteworthy
 218 that C_w derives from Gauss's theorem which involves the divergence of the water vapor
 219 flux field over the rectangular area.

220 Initially, equation 6 was used to calculate both zonal (qu) and meridional (qv) vertically
 221 integrated water vapour fluxes ($\text{kg m}^{-1} \text{s}^{-1}$; Brubaker et al., 1994). u and v are,
 222 respectively, the zonal and meridional wind components (m s^{-1}), q is the specific humidity
 223 (kg kg^{-1}), g is the gravitational constant (9.81 m.s^{-2}) and p is the atmospheric pressure (kg
 224 $\text{m}^{-1} \text{s}^{-2}$). The vertical integral considered the pressure levels between 3 (top of the
 225 atmosphere) and 1000 mb (surface). u , v and q are outputs of BAM.

226 The water vapour transport across the four walls T_e , T_w , T_s and T_n was computed using
 227 equation 7, which involves the line integral with integration limits defined by the latitudes
 228 (lat) and longitudes (lon) of the rectangular area.

$$229 \quad WB = C_w + (P - E + R) \quad (4)$$

$$230 \quad E = \frac{LE}{\lambda} \quad (5)$$

$$231 \quad \begin{cases} qu = \frac{1}{g} \int_{p1=3}^{p2=1000} u \cdot q \, dp \\ qv = \frac{1}{g} \int_{p1=3}^{p2=1000} v \cdot q \, dp \end{cases} \quad (6)$$

$$\left\{ \begin{array}{l}
T_e (lon=-40) = - \int_{lat=-25}^{lat=-15} qu dy \\
T_w (lon=-50) = \int_{lat=-15}^{lat=-25} qu dy \\
T_n (lat=-15) = - \int_{lon=-50}^{lon=-40} qv dx \\
T_s (lat=-25) = \int_{lon=-50}^{lon=-40} qv dx
\end{array} \right. \quad (7)$$

$$C_w = T_w + T_e + T_s + T_n \quad (8)$$

234 3. Results

235 3.1 IBIS-OFFLINE experiments

236 NAT and UP vegetation maps were used to perform IBIS-OFFLINE experiments.
237 Table 5 shows the mean difference between UP and NAT experiments over the area
238 between 25-15°S and 50-40°W, where major LULCC occurred (Figure 2). Overall,
239 similar changes were observed in early, neutral and late rainy season onset conditions due
240 to LULCC:

- 241 a) Albedo increased by up to 8%, meaning that more shortwave radiation is
242 reflected by the surface, **resulting in lower temperatures with consequent**
243 **decreases in longwave radiation emission by the surface.** It is noteworthy that
244 both incident shortwave and longwave radiation components were prescribed
245 in IBIS-OFFLINE experiments. Once less energy is available on the surface,
246 decrease in net radiation (shortwave and longwave net at the surface), sensible
247 and latent heat fluxes and surface temperature were verified. The reduction in
248 latent heat flux is attributed not only to the decreased energy available for soil
249 water evaporation, but also to differences in the transpiration rates between
250 C3 and C4 vegetation types. Specifically, C3 forest vegetation type (e.g.,
251 Atlantic Forest) has a **higher** transpiration rate compared to C4 pasture
252 vegetation type (**Taiz and Zeiger, 2010**). Similar results were identified by
253 Souza (2009) when the desertification was considered over the Semi-Arid
254 Northeast region of Brazil and also by Oliveira (2008) when deforestation was

255 considered over the east-Amazon. Evaporation reduction was also observed in
256 LULCC offline experiments over the southern-Amazon by Rezende et al.
257 (2022).

258 b) Soil water content decrease, although this reduction was relatively subtle. As
259 an offline experiment, the primary forcing was the precipitation initial
260 condition, which, in turn, was determined by the early, neutral, and late rainy
261 season onset conditions.

262 **3.2 BAM 3D experiments**

263 The difference between UP and NAT experiments (BAM 3D) for early, neutral,
264 and late onset years was analyzed over SA. Although LULCC is restricted within the
265 Brazilian territory, BAM 3D analysis was extended to the SA domain. This expansion is
266 justified by the effect perturbations such as LULCC have on remote regions through
267 nonlinear interactions via atmospheric circulation. Similar effects of vegetation changes
268 on remote regions have been identified in AGCM studies related to desertification in
269 northeast Brazil (Oyama and Nobre, 20004) and to Amazon deforestation (Nobre et al.,
270 2009).

271 To determine whether the differences between UP and NAT were attributed to
272 LULCC, Student's t-statistical test at a 95% confidence level was applied. Positive
273 (negative) differences indicate that the **variable** increased (decreased) in the UP
274 experiment compared to the NAT experiment, i.e., $UP > NAT$ ($UP < NAT$). Therefore,
275 the following analysis mentions positive (negative) differences as an increase (decrease)
276 of the **variable** due to LULCC.

277 In SON, precipitable water reduction (negative difference) was verified due to
278 LULCC. This reduction was noticeable over the northeast and southeast regions of SA
279 during early onset conditions (Figure 3a) and over the central-eastern part of SA in the
280 case of late onset (Figure 3o), with the statistical significance covering a larger
281 geographical area in the latter. **As consequence there is a decrease of water vapor**
282 **availability**. This, in turn, can suppress both cloud formation and precipitation over the
283 same region, specifically the central-eastern part of SA. **Similar condition of precipitation**
284 **reduction in BAM3D experiment was verified in Figure 1d, considering the GPCP**
285 **difference between late and early onset.**

286 An Outgoing Longwave Radiation (OLR) increase in UP experiments was
287 **simulated** over the central-east SA, with statistical significance in all three early, neutral,

288 and late onset years (Figure 3b, i, p). This OLR increase indicates a reduction in the
289 formation of high-top clouds due to LULCC. Consequently, less precipitation is expected
290 to occur over these areas. In the late onset, a statistically significant increase in OLR due
291 to LULCC was verified across the central-east SA (Figure 3p), similar to the precipitable
292 water reduction (Figure 3o). It implies that the northwest-southeast precipitation pattern,
293 typically associated with the SACZ, weakens due to LULCC during late onset. The
294 particular impact of LULCC in SACZ's life cycle is a gap for future studies that can be
295 assessed with daily output simulations.

296 A statistically significant decrease in OLR was verified across the northern and
297 northeastern regions of SA in the late onset year (Figure 3p). This decrease suggests a
298 compensatory signal to the south, i.e., a weak northwest-southeast cloud and precipitation
299 band. Therefore, these OLR differences exemplify the amplification of the precipitation
300 reduction pattern over SACZ region during late onset year (Figure 3q) attributed to
301 LULCC.

302 Precipitation reduction was verified over the study area and the central-northern
303 SA in the early onset (Figure 3c), over the central-eastern SA in the neutral onset (Figure
304 3j), and over a portion of **central and** southeastern SA in the late onset (Figure 3q). To the
305 south of the area with precipitation reduction, a precipitation increase was verified in all
306 three onset years (Figure 3c, j, q), with statistical significance observed only during the
307 late onset (Figure 3q). It indicates that LULCC had a suppressing (enhancing) effect on
308 precipitation near the SACZ (La Plata Basin) domain. The enhanced precipitation over
309 the La Plata Basin (Figure 3c, j, q) can be associated with the formation of transient
310 systems with more stationary behavior, a phenomenon frequently observed during the
311 rainy season, as reported by Raia and Cavalcanti (2008). In the late onset, a precipitation
312 increase was also verified over the northwest SA (Figure 3q) which further reinforces the
313 late onset pattern observed in **GPCP** data (Figure 1d).

314 A statistically significant increase in 850 hPa wind magnitude (Figure 3d, k, r)
315 was observed over the central, eastern and northeastern SA areas (indicated by positive
316 wind magnitude differences). This increase is associated with the SLP increase over
317 central-east SA. An SLP increase means greater pressure gradient, thus, a wind
318 acceleration. Additionally, the SLP increase can be linked to the displacement of the
319 subtropical South Atlantic high-pressure system closer to the continent, further increasing
320 the moisture transport from the ocean and the wind speed.

321 The increase in 850 hPa wind magnitude over SA can promote changes in the
322 northwesterly moisture flux which in turn can modify the position of the precipitating
323 systems associated with the rainy season such as the SACZ.

324 A statistically significant decrease in 2 m temperature was verified mainly over
325 the central-east in the early, neutral and late onset (Figure 3e, l, s). This reduction of up
326 to 2.5°C due to LULCC is attributed to the decrease in both net radiation and sensible
327 heat flux simulated in the IBIS experiments.

328 Positive SLP differences were verified over the central-east SA in all early, neutral
329 and late rainy season onset years (Figure 3f, m, t). However, these positive SLP
330 differences were statistically significant only in the late onset year when they were
331 verified throughout SA reaching the Atlantic Ocean between the coast of Argentina and
332 the northeast coast of Brazil (Figure 3t). The statistically significant positive SLP
333 differences indicate an SLP increase due to LULCC. The SLP increase over the Atlantic
334 Ocean (along the coast of Argentina) has the potential to weaken transient systems that
335 typically form in this cyclogenetic region (Gan and Rao, 1991; Reboita et al., 2010).
336 These transient systems play an important role in enhancing both soil and atmospheric
337 moisture (Raia and Cavalcanti, 2008; Talamoni et al., 2022), pre-conditioning the rainy
338 season onset. They also contribute to organize the cloudiness band over the SA and the
339 Atlantic Ocean (Raia and Cavalcanti, 2008). Therefore, weak transient systems can
340 contribute to further delay the rainy season late onset condition.

341 The SLP increase (Figure 3f, m, t) reiterates the suppressed precipitation due to
342 LULCC (Figure 3c, j, q). Consequently, an OLR increase is expected (Figure 3b, i, p).
343 While an OLR increase may suggest a net radiation increase due to incident shortwave
344 increase (cloud cover effect) it was not enough to offset the albedo increase contribution
345 (due to LULCC). Therefore, a statistically significant decrease in net radiation of up to
346 30 W m⁻² (negative differences) is observed over the southeast SA (Figure 3g, n, u). The
347 net radiation decrease is attributed to the albedo increase induced by LULCC. This effect
348 was confirmed by IBIS-OFFLINE experiments (Table 5), which reveal an increase in
349 incident shortwave radiation being reflected to the atmosphere.

350 In DJF, precipitable water decrease (negative difference) was simulated from
351 northwest to central-east SA in neutral onset year (Figure 4h). In the early onset, the
352 precipitable water decrease was shifted towards the north compared to the neutral onset
353 (Figure 4a). The statistically significant OLR increase in UP experiments across the
354 northwest and central-east in both early and neutral onset years (Figure 4a, h), reiterates

355 the precipitable water decrease over this region. Therefore, it is possible to associate that
356 the northwest-southeast precipitation pattern (typical of SAMS) is not enhanced in early
357 and neutral onset years when LULCC is considered.

358 A statistically significant precipitation reduction was verified over central-east in
359 the late onset (Figure 4q) associated with the SLP increase (Figure 4t) over the same
360 region which reinforces the suppression of cloud formation and precipitation (Figure 4p,
361 q). In addition, a precipitation increase was verified along the northwest, and northeast
362 SA in the late onset year (Figure 4q). This indicates a weakening of the summer monsoon
363 precipitation band (SACZ).

364 In the early onset year, precipitation was enhanced in parts of the northeast SA
365 (Figure 4c) where a statistically significant increase of the 850 hPa wind magnitude was
366 observed (Figure 4d). Thus, the enhanced wind magnitude (Figure 4d) contributed to the
367 precipitation increase over these areas (Figure 4c). On the other hand, a precipitation
368 decrease was verified over the central SA (Figure 4c). This pattern corroborates with the
369 precipitable water decrease which does not reinforce the SACZ. **Similarly, in the neutral**
370 **onset year the SACZ is weakened because of the simulated precipitation decrease all over**
371 **the central SA** (Figure 4j).

372 In DJF, although the 850 hPa wind magnitude increase across the central-east SA
373 (Figure 4d, k, r) **it** was lower in comparison with SON (Figure 3d, k, r). Observational
374 data (Zilli et al., 2019) and global warming projection (Soares and Marengo, 2009) studies
375 have associated the 850 hPa wind speed increase with the low-level jet intensification and
376 the SACZ displacement towards the south. The results obtained here shows the SACZ
377 intensity was affected by LULCC and its position was dependent on the considered rainy
378 season onset year.

379 Similar to SON, a statistically significant **2 m** temperature decrease was verified
380 mainly over central-east and northeast in the late onset during DJF (Figure 4s), which was
381 also verified in the potential temperature vertical profile (Figure 7). However, a
382 statistically significant increase in **2 m** temperature was observed in the central and
383 southeast SA, especially in the neutral onset (Figure 4l) where a precipitation decrease
384 (OLR increase) was also **simulated** (Figure 4i, j).

385 In DJF, SLP increase was observed in both early and late onset years (Figure 4f,
386 t). In the late onset, this SLP increase was prominent in central-east SA (Figure 4t). This
387 suggests that LULCC does not promote the typical summer monsoon pattern

388 characterized by a reduction in SLP across the continent. Thus, it indicates that LULCC
389 can change the SAMS features.

390 The areas where statistically significant reductions in net radiation were observed
391 during DJF decreased compared to SON, primarily concentrated in the southeast SA
392 (Figure 4g, n, u). In DJF, statistically significant increase in net radiation was verified
393 over parts of the northeast SA (Figure 4g, n, u). Furthermore, a decrease in OLR and
394 increase in precipitation was verified over the northeast SA (Figure 4p, q). These findings
395 indicate that a subsequent increase in soil water content reduces the surface albedo, thus,
396 increase the soil heat capacity. As a result, more incident shortwave radiation is absorbed,
397 leading to an increase in surface net radiation.

398 Figure 5 shows a surface water budget analysis similar to the one applied by
399 Talamoni et al. (2022), for BAM experiments over the area between 25-15°S and 50-
400 40°W. The aim was to identify the contribution of each WB component by assessing the
401 difference between UP and NAT experiments. In SON (Figure 5a), C_w was the main
402 contributor to the water budget of all three onset years. The moisture comes mainly from
403 the ocean and from frontal systems. C_w was greater in UP experiments of both late and
404 neutral onset years. In addition, C_w increase to the continent can be associated with the
405 subtropical South Atlantic high-pressure system displaced closer to SA indicated by the
406 SLP increase (Figure 3 m, t). On the other hand, the precipitation was lower in UP
407 experiments in all years. Despite the increase in C_w , convective processes were inhibited
408 due to increases in SLP associated with a dry and cold vertical profile (Figure 7).

409 In the early onset year, both P and C_w were lower in UP experiments, resulting in
410 a reduced WB. It can be associated with the SLP decrease over the Atlantic Ocean which
411 contributed to inhibit the frontal systems of advancing towards the area between 25-15°S
412 and 50-40°W, leading to a reduction in C_w .

413 The early and neutral onset years WB was higher (lower) in UP experiments in
414 DJF (Figure 5b), mainly due to R contributions. The R increase is associated with the
415 reduction of water absorption and interception by pasture vegetation, thereby limiting the
416 amount of water available for soil infiltration. Additionally, E increase suggests that the
417 exposed soil is undergoing enhanced water loss to the atmosphere.

418 The late onset year WB was lower in UP experiments (Figure 5b), particularly due
419 to C_w and P contributions. The C_w decrease is associated with SLP increase over central-
420 east SA and in the Atlantic Ocean (Figure 4 t) disfavours the advance of frontal systems
421 that organizes convection and configure SACZ events. SLP increase also contribute to a

422 more stable atmosphere (colder and drier profile in Figure 7) which suppresses convection
423 and consequently, reduces P.

424 4. Summary and Conclusions

425 This study investigated how LULCC affects the SA rainy season by implementing
426 an updated vegetation map that considers the LULCC over the Brazilian territory with
427 early 2000s deforestation rates into IBIS and BAM models. Major differences between
428 NAT and UP vegetation maps were verified over the area between 25-15°S and 50-40°W
429 where both Atlantic Forest and Cerrado biomes were replaced by pasture. The numerical
430 experiments were performed with two vegetation maps (NAT and UP) on two
431 frameworks: offline using the land-surface model (IBIS) and online using the BAM.
432 Three rainy season onset conditions were considered in the experiments: early (2006),
433 neutral (2004), and late (2008) rainy season onset.

434 In IBIS-OFFLINE experiments, similar changes in surface variables induced by
435 LULCC were observed in all three rainy season onset years. These changes are
436 summarized in the green boxes of the diagram in Figure 6 (based on Table 5). The shift
437 from C3 forest to C4 pasture vegetation types (LULCC), particularly over the area
438 between 25-15°S and 50-40°W, triggered an immediate rise in albedo (exposed land has
439 higher albedo). Additionally, the shift led to a decrease in surface roughness due to the
440 shorter vegetation type. As a result of these changes, more shortwave radiation is reflected
441 by the surface, leading to a decrease in the available energy. Consequently, net radiation,
442 surface heat fluxes (both latent and sensible), and surface temperature all decreased.

443 The surface-atmosphere feedback due to LULCC was assessed in BAM
444 experiments, summarized in the pink boxes in Figure 6. While major statistically
445 significant differences between UP and NAT experiments were observed in the late rainy
446 season onset year and during SON, similar patterns were identified in the area 25-15°S
447 and 50-40°W for the early and neutral onset years (Table 6). The reduction in both latent
448 and sensible heat fluxes contributed to a decrease in precipitable water and 2 m
449 temperature, respectively. It contributed to setting up a drier and colder (more stable)
450 atmosphere as depicted in Figure 7. These atmospheric changes resulted in less cloud
451 formation and reduced precipitation, accompanied by an increase in OLR. Furthermore,
452 SLP and low-level wind increased as direct responses to the reduction in 2 m temperature
453 and surface roughness, respectively. These results indicate that over the area where major

454 LULCC occurred (25-15°S and 50-40°W), the behavior of the rainy season was modified.
455 Precipitation was suppressed through surface-atmosphere feedback mechanisms,
456 particularly in the late rainy season onset year and SON, when there is a greater
457 dependence on local forcing.

458 Overall, UP experiments exhibited a drier and colder vertical profile, with the
459 most significant differences in the late rainy season onset during SON. This drier
460 atmospheric profile induced by LULCC resembles the dry atmospheric condition
461 (reduced soil moisture and precipitation, in addition to increased sensible heat flux)
462 observed in late onset years reported by Talamoni et al. (2022) over central-east SA and
463 by Fu and Li (2004) over the southern Amazon. **Future studies can investigate the
464 hypothesis that LULCC might delay the onset of the rainy season by amplifying the
465 atmospheric dry pattern observed during late onset years.** This hypothesis agrees with two
466 studies that investigated the role of latent and sensible heat fluxes on SAMS development.
467 Silva (2012) and Garcia (2010) observed surface heating over central SA preceding to the
468 rainy season onset. This heating is important to increase both sensible and latent heat
469 fluxes and to build up instability in the lower troposphere. From the heating, SLP
470 decreases, promoting low-level mass convergence and upward vertical movement. **In
471 addition, we also suggest that future studies can perform long-term simulations to assess
472 long-term changes in SAMS features.**

473 In this study, we focused on identifying the local and non-local impacts LULCC
474 has on both surface and atmospheric variables focusing on Brazil. In future studies, we
475 suggest a further investigation of the mechanisms responsible for differences between
476 NAT and UP experiments at the outskirts of the Brazilian territory. Giles et al. (2022)
477 conducted a similar investigation, examining how soil moisture variability over
478 southeastern South America and eastern Brazil affected the regional circulation and led
479 to changes in precipitation over northeastern Argentina.

480 In conclusion, this study represents the first endeavor to incorporate an updated
481 and realistic vegetation map of the Brazilian territory into BAM. The numerical
482 experiments highlighted the importance of considering LULCC in vegetation maps.
483 Therefore, we expect that future BAM experiments are performed with the UP vegetation
484 map proposed here, and we hope this study motivates future implementations of even
485 more realistic and up-to-date vegetation maps in AGCMs.

486 **Acknowledgment**

487 We thank two anonymous reviewers for providing helpful comments on the paper. This
488 paper had support of *Coordenação de Aperfeiçoamento de Pessoal de Nível Superior*
489 (CAPES). The first author (ILT) was supported by CAPES (process 88887.354679/2019-
490 00). Acknowledgments also to CLIMAX-FAPESP-Belmont-2015/50687-8. The third
491 author (IFAC) thanks CNPq- Project 306393/2018-2. The fifth author (JB) was supported
492 by the European Research Council (ERC) under the European Union's Horizon 2020
493 research and innovation programme (DECAF project, Grant agreement No. 771492) and
494 United Kingdom Research and Innovation (UKRI) Future Leaders Fellowship (Grant
495 Ref: MR/X034097/1). We thank CPTEC/INPE for the technical and infrastructure
496 support related to the Post-Graduation Program. Data was obtained from available
497 sources as noted by references on Table 1: GLDAS, ERA5, NCEP-NOAA and GPCP.

498 **Conflict of interest**

499 The authors declare no competing interests.

500

501 **Data availability**

502 GLDAS, ERA5, RADS and GPCP were used to support the findings of this study. These
503 datasets are all available in the public domain. GLDAS is openly available at
504 [https://disc.gsfc.nasa.gov/datasets/GLDAS_NOAH025_M_2.1/summary?keywords=GLDAS]. ERA5 can be found at [<https://doi.org/10.24381/cds.adbb2d47>]. RADS is openly
506 available at [<https://climatology.tamu.edu/research/Rainy-and-Dry-Season-RADS.html#:~:text=What%20is%20RADS%3F,the%20rainy%20and%20dry%20seasons.>]. GPCP can be accessed at [<http://doi.org/10.7289/V56971M6>]. NOAA NCEP sea
509 surface temperature data is a product available under request at [<https://www.ncei.noaa.gov/products/optimum-interpolation-sst>]. The vegetation maps
511 used in the study are available from the corresponding author upon reasonable request.

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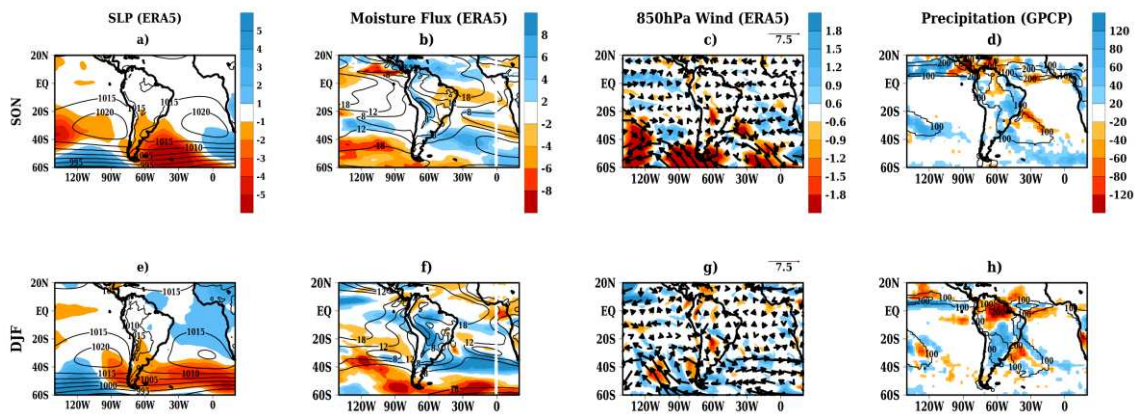
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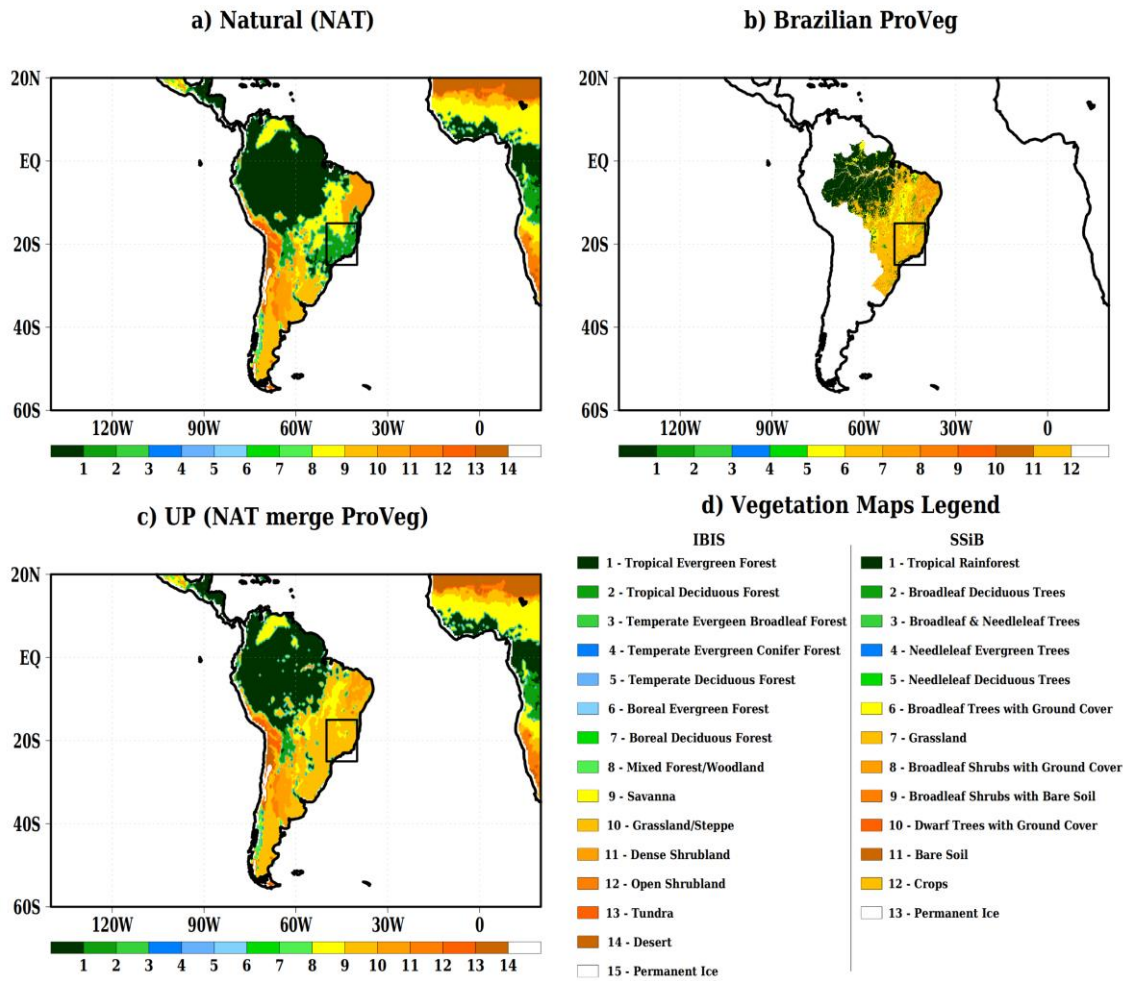
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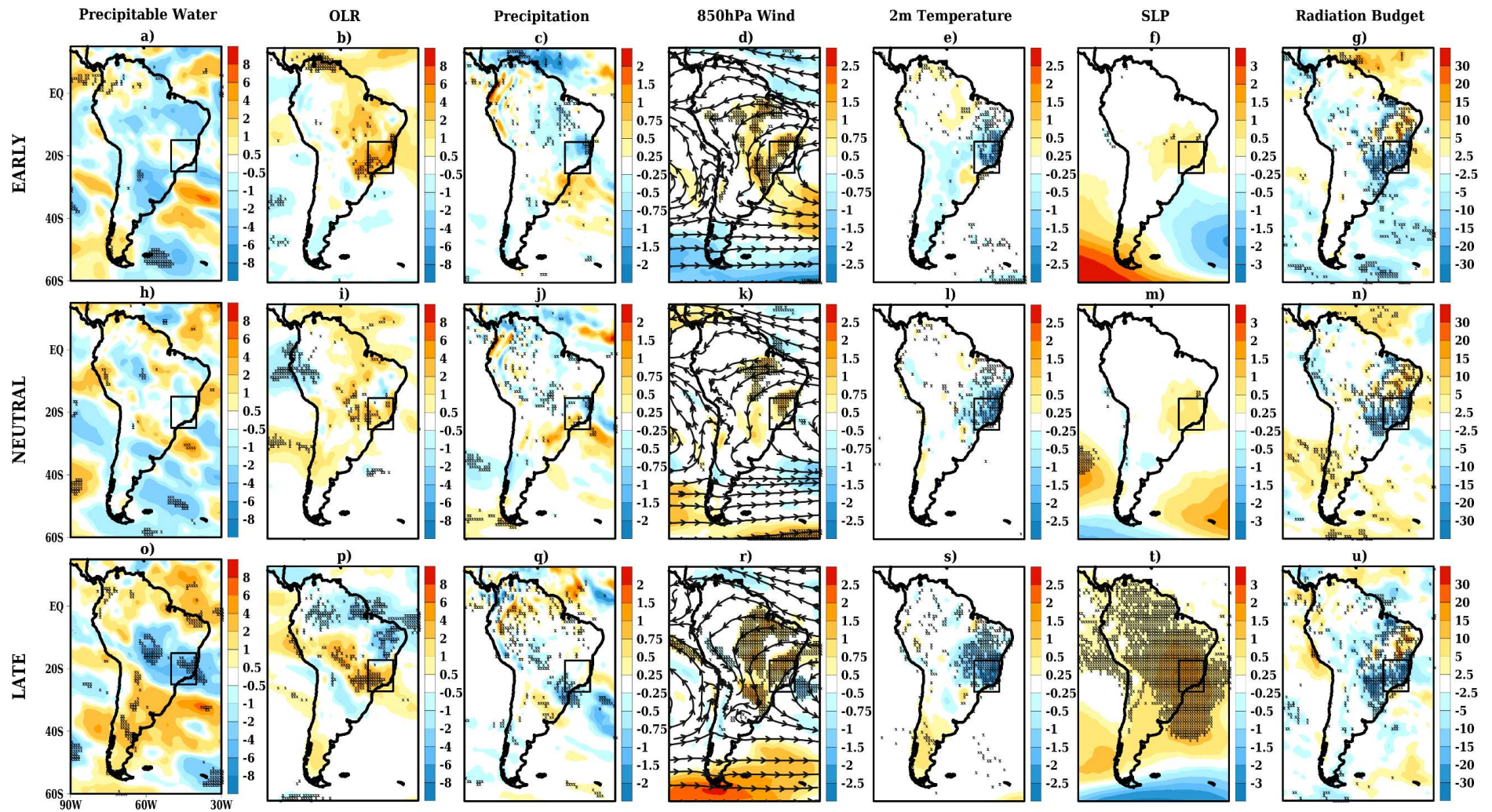
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741 **Figure 1** – ERA5: (a)-(e) sea level pressure (shading, hPa) and climatology (contours,
 742 hPa), (b)-(f) moisture flux magnitude anomaly (shading, $10^{-5} \text{ kg m}^{-1} \text{ s}^{-1}$) and moisture flux
 743 magnitude climatology (countour, $10^{-5} \text{ kg m}^{-1} \text{ s}^{-1}$), (c)-(g) 850 hPa wind magnitude
 744 anomaly (shading, m s^{-1}) and vector difference (arrows, m s^{-1}). GPCP: (d)-(h)
 745 precipitation anomaly (shading, mm) and climatology (contour, mm). The anomaly
 746 represents the differences between the early and late onset years of SON and DJF. The
 747 climatology ranges from 1989 to 2015.

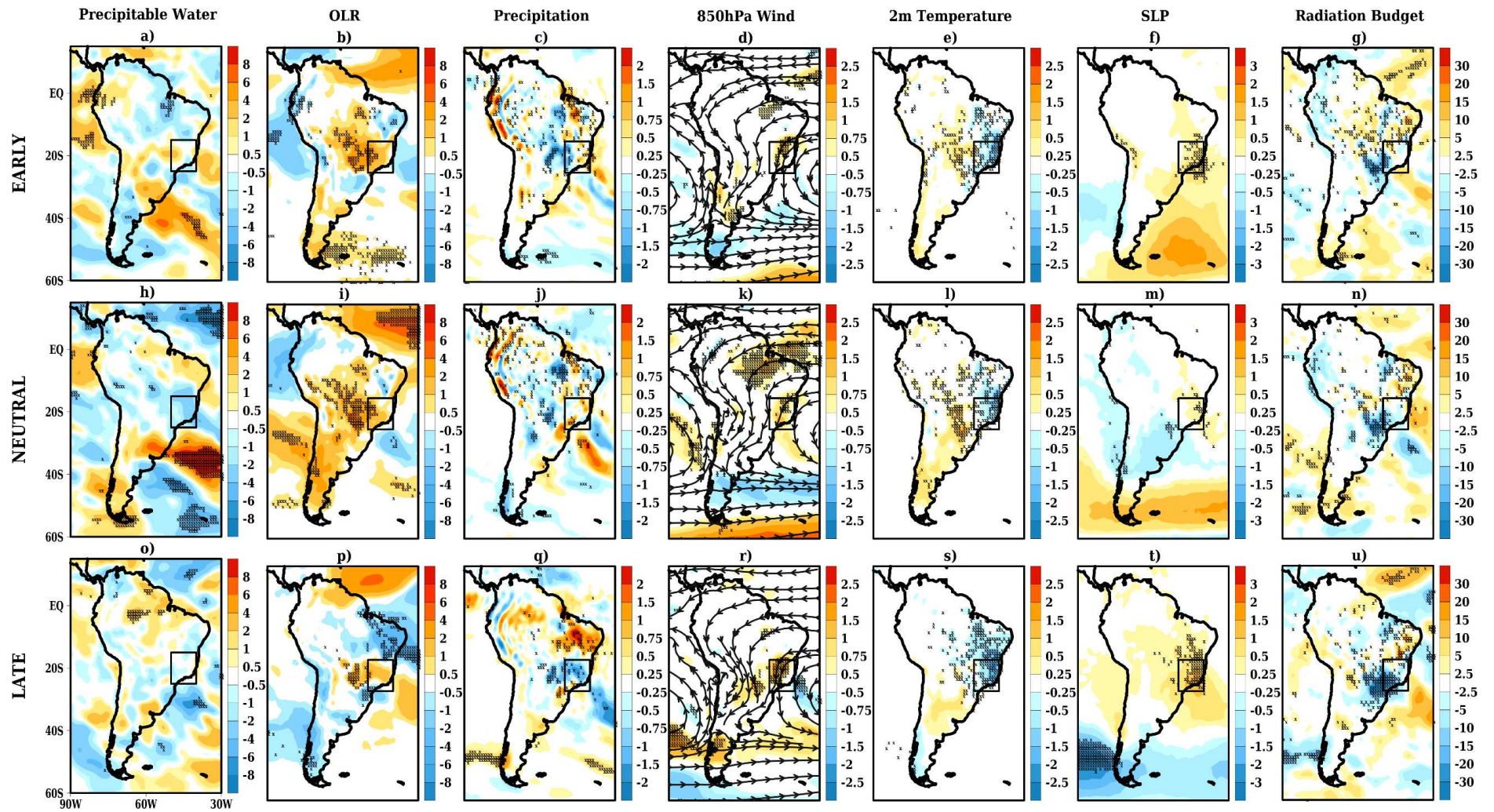


748 **Figure 2** – (a) NAT vegetation map, (b) ProVeg vegetation map, (c) UP vegetation map
 749 that merges (a) and (b) to account for LULCC over the Brazilian territory. (a) and (c)
 750 are the vegetation maps used in the numerical experiments performed with IBIS and BAM.
 751 The outlined box in black is the area between (25-15°S and 50-40°W), where major
 752 LULCC occurred: Atlantic Forest (Southeast and south of Northeast regions of Brazil)
 753 and Cerrado (Central-East regions of Brazil) biomes were replaced by pasture.

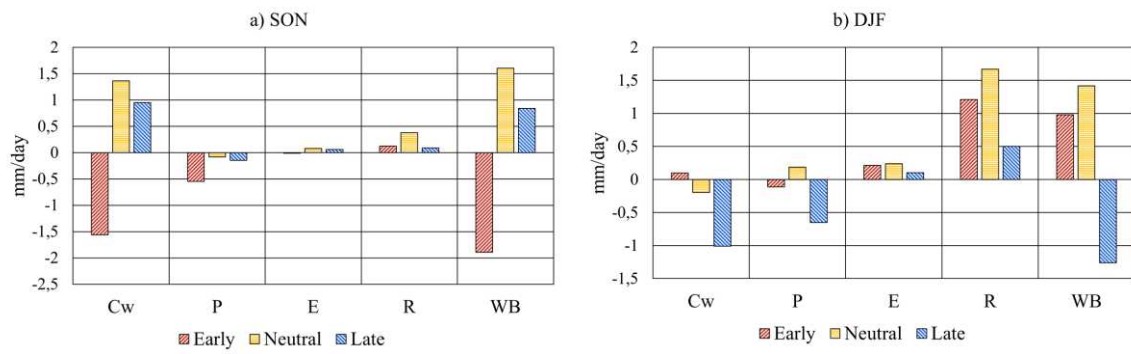


754 **Figure 3** – (a)-(h)-(o) precipitable water (shading), (b)-(i)-(p) OLR (shading, $W m^{-2}$), (c)-(j)-(q) precipitation (shading, $mm day^{-1}$), (d)-(k)-(r) 850
755 hPa wind magnitude (shading, $m s^{-1}$) and mean wind flow (streamlines), (e)-(l)-(s) 2 m temperature (shading, $^{\circ}C$), (f)-(m)-(t) SLP (shading, hPa),

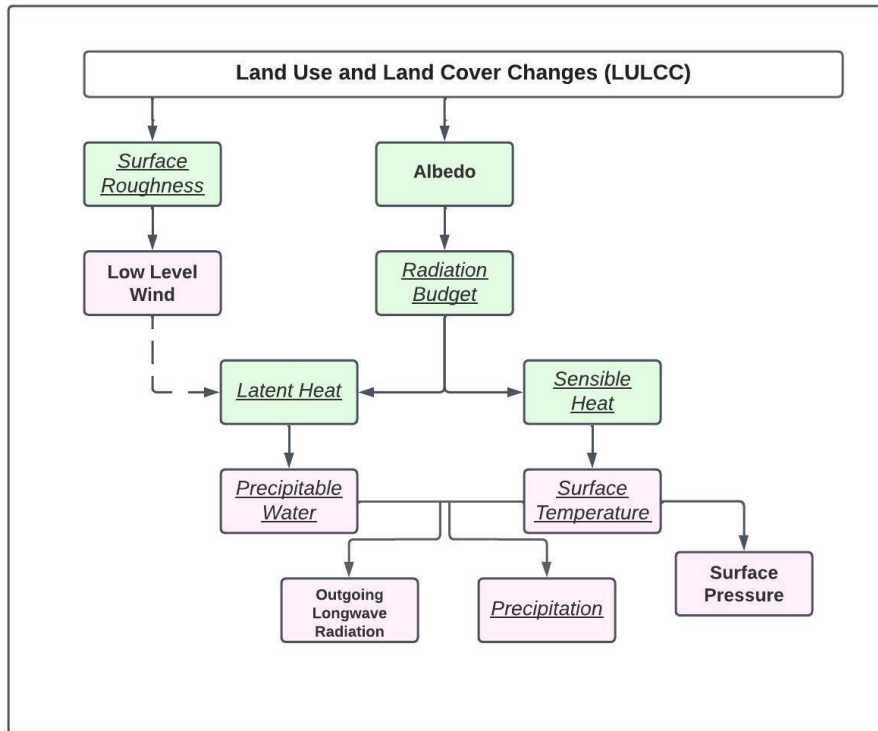
756 and (g)-(n)-(u) net radiation (shading, W m^{-2}) differences between UP and NAT experiments performed with BAM in SON at early, neutral and
757 late rainy season onset years. Hatching areas indicate statistical significance at a 95% confidence level. The outlined box in black is the area
758 between $(25\text{-}15^\circ\text{S}$ and $50\text{-}40^\circ\text{W}$), where major LULCC was identified.



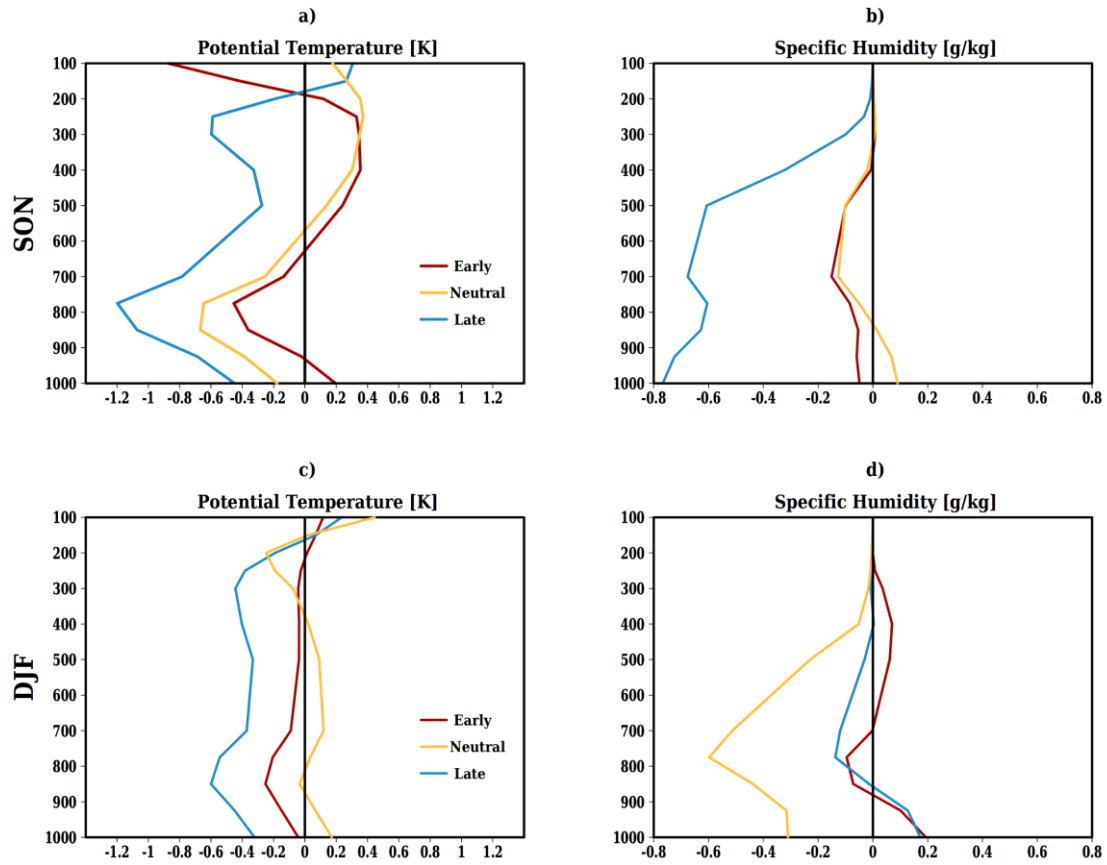
759 **Figure 4** - Same as Figure 3, but in DJF.



760 **Figure 5** – (a) SON, (b) DJF differences between UP and NAT experiments for each
 761 surface water budget component (mm day^{-1}) averaged over the area between $25\text{-}15^\circ\text{S}$ and
 762 $50\text{-}40^\circ\text{W}$.



763 **Figure 6** - IBIS-OFFLINE and BAM experiments **variables** modifications due to
 764 LULCC. Green (pink) boxes show the physical **variables** assessed by IBIS-OFFLINE
 765 (BAM 3D) experiments due to LULCC. The underlined (bold) **variables** decreased
 766 (increased) due to LULCC. The continuous (dashed) arrows indicate a positive (negative)
 767 correlation between the **variables**.



768 **Figure 7:** Vertical profile of the difference between UP and NAT (BAM) experiments
 769 of (a)-(c) potential temperature (K) and (b)-(d) specific humidity (g kg^{-1}). The profiles
 770 are averages over the area between $25\text{-}15^\circ\text{S}$ and $50\text{-}40^\circ\text{W}$ at both seasons SON (a, b)
 771 and DJF (c, d).

Dataset	Type	Temporal Resolution/ Coverage	Horizontal Resolution	Variables	References
GLDAS	Rain-gauge and satellite data ingested by surface modeling and data assimilation techniques	3 hours/ July 2004 - March 2009	0.25° x 0.25° ~25 km	sea level pressure, precipitation, longwave incident radiation, shortwave incident radiation, temperature, surface wind, specific humidity, and soil water content	Beaudoing and Rodell (2020)
ERA5	Reanalysis	Hourly/ 1981 to 2010	0.25° x 0.25° ~25 km	sea level pressure, U and V wind component, temperature, specific humidity and orography	Hersbach et al. (2023)
NCEP-NOAA	Optimum interpolation analysis using satellite and in situ data	Daily/	1.0° x 1.0°	Sea Surface Temperature	Huang et al. (2020)
GPCP	Rain-gauge and satellite data estimates	Monthly/ 1981 to 2010	2.5° x 2.5°	Precipitation	Adler et al. (2016)

772 **Table 1:** Data description used in this study. ERA5 dataset has 37 vertical levels.

Exp.	Onset Condition	Simulation Period	Vegetation Map
E01	Early Year	01/07/2006 - 28/02/2007	
N01	Neutral Year	01/07/2004 - 28/02/2005	NAT
L01	Late Year	01/07/2008 - 28/02/2009	
E02	Early Year	01/07/2006 - 28/02/2007	
N02	Neutral Year	01/07/2004 - 28/02/2005	UP
L02	Late Year	01/07/2008 - 28/02/2009	

773 **Table 2:** IBIS-OFFLINE experiments. Hourly output frequency and continuous simulations.

Physical Process	Configuration
Cloud Microphysics	Double-moment microphysics scheme (Morrison et al., 2009)
Land surface	Dynamic vegetation model - IBIS v.2.6 (Foley et al., 1996), implemented and adapted by Kubota (2012)
Shortwave radiation	CLIRAD-SW (Chou and Soares, 1999) modified by Tarasova and Fomin, 2000
Longwave radiation	CLIRAD-LW (Chou et al., 2001)
Planetary Boundary Layer (PBL)	Turbulence scheme for vertical diffusion of momentum, heat, and moisture (Bretherton and Park, 2009)
Deep convection	Arakawa-Schubert simplified and reviewed (Han and Pan, 2011)
Aerosol optical depth	Yu et al. (2006)
Thermal plume for PBL	Rio and Hourdin (2008)
Gravity wave drag	Webster et al.'s (2003) scheme with low-level blocking

774 **Table 3:** Physical processes configurations of BAM v.2.2.1.

Exp.	Initial Condition Date	Simulation Period	Exp.	Initial Condition Date	Simulation Period
Early Onset - 2006					
C1.1	2006 07 01 12	July - March	C1.6	2006 10 01 12	October - May
C1.2	2006 07 02 12		C1.7	2006 10 02 12	
C1.3	2006 07 03 12		C1.8	2006 10 03 12	
C1.4	2006 07 04 12		C1.9	2006 10 04 12	
C1.5	2006 07 05 12		C1.10	2006 10 05 12	
Neutral Onset - 2004					
C2.1	2004 07 01 12	July - March	C2.6	2004 10 01 12	October - May
C2.2	2004 07 02 12		C2.7	2004 10 02 12	
C2.3	2004 07 03 12		C2.8	2004 10 03 12	
C2.4	2004 07 04 12		C2.9	2004 10 04 12	
C2.5	2004 07 05 12		C2.10	2004 10 05 12	
Late Onset - 2008					
C3.1	2008 07 01 12	July - March	C3.6	2008 10 01 12	October - May
C3.2	2008 07 02 12		C3.7	2008 10 02 12	
C3.3	2008 07 03 12		C3.8	2008 10 03 12	
C3.4	2008 07 04 12		C3.9	2008 10 04 12	
C3.5	2008 07 05 12		C3.10	2008 10 05 12	

775 **Table 4:** BAM experiments design. A 2-month spin-up was considered for each simulation
776 period. Monthly output frequency experiments. The initial condition date is in the format
777 year/month/day/hour.

Surface Variables	UP - NAT (SON)			UP - NAT (DJF)		
	Early	Neutral	Late	Early	Neutral	Late
Albedo	0,088	0,083	0,084	0,080	0,079	0,081
Latent heat flux (W m ⁻²)	-14,09	-9,51	-8,58	-11,98	-16,47	-12,20
Sensible heat flux (W m ⁻²)	-17,28	-25,78	-25,01	-14,94	-14,61	-17,65
Net radiation (W m ⁻²)	-17,17	-20,35	-20,32	-16,06	-17,13	-21,17
Soil water content	-0,006	-0,002	-0,001	0,004	-0,006	-0,003
Surface Temperature (°C)	-0,24	-0,02	-0,05	-0,16	-0,17	0,10

778 **Table 5:** Mean difference between UP and NAT (IBIS OFFLINE) experiments over the
779 area between 25-15°S and 50-40°W in SON and DJF. Highlighted in blue (red) are the
780 negative (positive) differences which represent a decrease (increase) of the respective
781 surface parameter in UP experiment compared to NAT experiment.

Atmospheric Variables	UP - NAT (SON)			UP - NAT (DJF)		
	Early	Neutral	Late	Early	Neutral	Late
Precipitable water (mm day ⁻¹)	-0,52	-0,47	-4,21	0,21	-1,98	-0,20
Outgoing Longwave Radiation (W m ⁻²)	3,56	1,21	2,09	1,28	1,01	0,60
Precipitation (mm day ⁻¹)	-0,55	-0,06	-0,19	-0,11	0,19	-0,65
Sea Level Pressure (hPa)	0,53	0,51	1,47	0,51	0,21	0,92
850hPa wind speed (m s ⁻¹)	0,64	0,66	0,77	0,55	0,82	0,71
Surface Temperature (°C)	-0,91	-1,09	-1,32	-0,48	-0,36	-0,73
Net Radiation (W m ⁻²)	-10,41	-9,18	-10,40	-1,30	-3,06	-7,57

782 **Table 6:** Mean difference between UP and NAT (BAM) experiments over the
783 area between 25-15°S and 50-40°W in SON and DJF. Highlighted in blue (red) are the
784 negative (positive) differences which represent a decrease (increase) of the respective
785 atmospheric parameter in UP experiment compared to NAT experiment.

