Impact of Tropical Deforestation and Forest Degradation on Precipitation over Borneo Island

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ABSTRACT

Southeast Asian tropical rain forests in the Maritime Continent are among the most important biomes in terms of global and regional water cycling. How land use and land cover change (LULCC) relating to deforestation and forest degradation alter the local hydroclimate over the island of Borneo is examined using the Weather Research and Forecasting (WRF) Model with an appropriate land surface model for describing the influence of changes in the vegetation status on the atmosphere. The model was validated against precipitation data from Tropical Rainfall Measuring Mission (TRMM) satellite 3B42 measurements. A main novelty in this analysis is that the diurnal cycle of precipitation over the island, which is a dominant climatic characteristic of the Maritime Continent, was successfully reproduced. To clarify the impact of the LULCC on the precipitation regimes over the island, numerical experiments were performed with the model that demonstrated the following. Deforestation that generates high albedo areas, such as bare lands, would induce a reduction in precipitation because of reductions in evapotranspiration, convection, and horizontal atmospheric moisture inflow. On the other hand, a decrease in evapotranspiration efficiency without changing the surface albedo could increase precipitation due to an increase in convection and horizontal atmospheric moisture inflow in compensation for the decrease in evapotranspiration. In detail, on the Maritime Continent, through changes in the land surface heating process and land-sea breeze circulation, the LULCC would impact the amplitude of the diurnal precipitation cycle in each region as defined according to the distance from the coast, resulting in changes in the precipitation regimes over the island.

1. Introduction

Tropical forests are a major source of global hydrologic fluxes, profoundly influencing both global and regional climates (see Kumagai et al. 2016). Humans have been modifying tropical forest land cover for food and energy production and for the development of tropical countries. Consequently, such modifications, that is, land use and land cover change (LULCC), are being combined with climate change and are anticipated to impact the climate on local, regional, and even global scales via

teleconnections (Werth and Avissar 2002; Medvigy et al. 2013; Lawrence and Vandecar 2014; Mahmood et al. 2016). Among the LULCC-driven climate variabilities, the alteration of precipitation regimes in the tropics has been examined in many previous studies: in Amazonia and Africa, convective activity in the dry season weakened after deforestation, leading to a strong intensification of drought (Voldoire and Royer 2004), and in Amazonia, above-normal (below normal) annual precipitation can enhance (suppress) the vegetation's productivity, resulting in an increase (decrease) in the subsequent year's precipitation (Wang et al. 2011). Lawrence and Vandecar (2014) summarized difficulties in projecting the precipitation change induced by tropical deforestation on continental and local scales; for example, precipitation could be reduced or enhanced in accordance with the size and state of deforestation (a single

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large patch is similar to distributed patches). Here, we must note that, in turn, such LULCC-driven hydroclimate change could lead to significant negative impacts on tropical forest ecological patterns and processes (see Malhi et al. 2009; Kumagai and Porporato 2012) and limitations to agricultural productivity in some regions (Lawrence and Vandecar 2014).

Southeast Asian tropical forests have the highest relative deforestation rate in the world (Canadell et al. 2007). Also, on the island of Borneo, LULCC, that is, deforestation and forest degradation, has been among the most critical issues over the past several decades (Bryan et al. 2013; Gaveau et al. 2013, 2014), and might have induced the observed decadal decline of annual precipitation (see Kumagai et al. 2013). As the Southeast Asian tropics consist of the Maritime Continent, whose geographical characteristics play a significant role in the formation of large-scale circulations (Mabuchi et al. 2005), the hydroclimate in this region may respond to the LULCC differently than do large continents such as South America and Africa. Zhang et al. (2001) showed that deforestation would induce a decrease in precipitation over the Southeast Asian tropics. On the contrary, Gotangco Castillo and Gurney (2013) suggested that deforestation could enhance precipitation over the Southeast Asian tropics, possibly because water vapor for precipitation can be supplied from the ocean that surrounds islands in the Maritime Continent.

Smaller tropical islands, in which orographic precipitation hardly occurs, tend to be dry in a future warmer climate (Karnauskas et al. 2016). On the other hand, on larger islands, orographic precipitation should be dominant, and water vapor for forming the precipitation is likely supplied from the ocean that surrounds the islands (Sobel et al. 2011). Previous studies (e.g., Ichikawa and Yasunari 2006; Kanamori et al. 2013) have claimed that on Borneo, there is a pronounced diurnal cycle of convection and precipitation strongly influenced by geographical traits, such as the thermal contrast between the islands, ocean, and mountain-valley circulations, and modulated by large-scale intraseasonal oscillations in the tropical atmosphere [e.g., the Madden-Julian oscillation (MJO)]. Thus, a computation grid size of 20 km, which is currently among the finest scales for climate simulation with general circulation models (GCMs), can be assumed to be sufficient for simulating only thermally induced local circulations, but, in the case of simulations of the precipitation regimes in Borneo, is insufficient for reproducing the diurnal cycle of the convective system, which is coupled with the land-sea, mountain-valley, and large-scale circulations (see Hara et al. 2009). Hara et al. (2009) simulated the diurnal cycle of precipitation over Borneo using a 3-km horizontal grid with a regional

climate model. The simulated precipitation shows a detailed cloud and precipitation process that cannot be simulated by coarse-grid simulations. To our knowledge, despite many numerical studies on the impact of the LULCC on the local and global climate using GCMs in the past several decades, no models with sufficiently fine resolution have been applied to numerical experiments to simulate such complicated precipitation processes on the Maritime Continent, except for a few GCMs with huge supercomputers, such as the nonhydrostatic icosahedral atmospheric model (NICAM) model (Satoh et al. 2014; Kodama et al. 2015; Miyamoto et al. 2016).

Our goal is to investigate how the local climate, especially the precipitation regime, on Borneo will respond to LULCC. Toward this goal, we use a regional climate model with a fine horizontal resolution sufficient to simulate cloud and precipitation processes, which are driven by geographical traits unique to Borneo, and conduct numerical experiments with scenarios of varying degrees of deforestation and degradation. Prior to assessing the impact of the LULCC on the hydroclimate, the model is first validated with satellite rainfall measurements over the Maritime Continent.

2. Methodology

a. Site description

Borneo (1°00'N, 114°00'E), our simulation object, is the third-largest island in the world $(743\,330\,\text{km}^2)$ with high mountains (maximum altitude 4095 m; see Fig. 1). Borneo was famous for its majestic rain forests. In the 1950s, more than 80% of its total land area was covered with pristine forest; however, the high deforestation rate $(1.7\% \text{ yr}^{-1})$, which is almost double that of the already intense deforestation rate of the entire Southeast Asian region, has resulted in an estimation of $\sim 50\%$ forest cover (Langner et al. 2007). The dominant tree species is dipterocarp, which is among the most valuable timber species globally. This has led to intense logging pressure on Borneo. The land cover areas categorized as "degraded forest and regrowth," "cultivation forest mosaic," and "dry/wet bare soil; grasslands; agriculture" reached up to 33 million ha, \sim 45% of the total land area of Borneo (Langner et al. 2007).

The long-term daily grid precipitation datasets (APHRODITE's Water Resources, available via http:// www.chikyu.ac.jp/precip/; Yatagai et al. 2012) showed a large amount of precipitation over Borneo, that is, the spatiotemporal average (in 2000–07 and over the island) is \sim 2000 mm yr⁻¹. Considering this drastic deforestation and forest degradation, it is logical to anticipate its impact on the regional hydroclimate; in reality, APHRO-DITE suggests a significant decline in precipitation over



FIG. 1. (a) Domains for the simulations, (b) topography, (c) regions for analysis: inland (light gray), coastal land (gray), and coastal sea (dark gray), and the land cover types for (d) Control and 0.2Gcmax and (e) Barren-1. The black area in (e) denotes the lowland area below an altitude of 100 m MSL. Land cover type in the black area in Barren-1 is modified into bare land. Land cover type in Barren-2 assumes all areas over Borneo are bare land. The land cover types depicted in colors in (d) and (e) are shown in the legend by colors and numbers: 5, cropland/grassland mosaic; 6, cropland/woodland mosaic; 7, grassland; 8, shrubland; 9, mixed shrubland/grassland; 10, savanna; 11, deciduous broadleaf forest; 13, evergreen broadleaf forest; 15, mixed forest; and 16, water bodies.

Borneo in the period from 1951 to 2007 to be from \sim 2600 to 1900 mm yr⁻¹ (Kumagai et al. 2013).

b. The model

The model used here is the Advanced Research version of the Weather Research and Forecasting (WRF) Model (ARW, version 3.5.1; Skamarock et al. 2008), including the Noah land surface model (Mitchell 2005). Parameterization schemes, the area of model domains, and the simulation period in this study were similar to those in Hara et al. (2009), except for the boundary conditions and the version of the WRF Model. Two-way nesting was employed: the outer domain (D01) has 142×142 grid points with 17.5-km grid spacing, and the inner domain (D02) has 511×541 grid points with 3.5-km grid spacing (Fig. 1a). Both domains have 35 vertical layers from the ground surface to the pressure level of 50 hPa. As for the cloud microphysics scheme, we employed the WRF singlemoment 6-class scheme. Cumulus parameterization was used in D01 (the Kain-Fritsch convective scheme) but not in D02. The Dudhia scheme was used for longwave radiation and shortwave radiation. The Mellor-Yamada-Janjić scheme was employed for the scheme of turbulent kinetic energy in the planetary boundary layer.

c. Simulations

Computations were performed during the period from 1200 local time (LT) 25 March to 1800 LT 30 April 2004 (35 days). As described in Hara et al. (2009), no tropical cyclones or active MJO convection areas (i.e., in the MJO inactive season) were observed over Borneo throughout the simulation period. The anomaly of the Niño-3.4 index for the period is 0.06, which means no significant El Niño and La Niña events, according to the National Oceanic and Atmospheric Administration/Climate Prediction Center. In general, precipitation amount in the MJO inactive season is less than in the MJO active season, so the simulated impact of land use change is expected to be clearer than in the MJO active season. On the Maritime Continent, year-to-year variability of precipitation amount is controlled by seasonal changes brought by MJO and/or El Niño. Of the 35 days, the first 5.5 days in March 2004 were used for spinup, and the following 30 days in April 2004 were an analysis object. The initial and boundary conditions for the simulation are found in the ERA-Interim reanalysis dataset (Dee et al. 2011). Types of topography (Fig. 1b) and land cover (Fig. 1d) were provided as defaults in the ARW version 3.5.1. We note that the dominant species in the types of land cover on the island is broadleaf evergreen (Figs. 1d,e). The precipitation simulations were validated using the 3-hourly data of the Tropical Rainfall Measuring Mission (TRMM) satellite 3B42v7 datasets (NASA

Goddard Earth Sciences Data and Information Services Center, available at https://disc.gsfc.nasa.gov/).

Figure 1c shows the three separated regions for analysis: inland, coastal land, and coastal sea. The inland and the coastal land areas are almost the same, and the coastal sea area is about 1.5 times that of the other two land areas. We constructed four types of numerical experiments. Both 1) Control and 2) 0.2Gcmax assume actual land cover types (Fig. 1d), but the maximum stomatal conductance (Gcmax) in 0.2Gcmax is 0.2 times that in Control. In 3) Barren-1 and 4) Barren-2, land cover types in the lowland area below 100 m above sea level (Fig. 1e) and in all areas of the island were changed to bare land, respectively. Here, note that all the numerical experiments were performed in conditions of ample soil moisture, that is, no soil moisture limitation on stomatal conductance, and that the multiplier 0.2 in 0.2Gcmax was determined so that evapotranspiration over the island in 0.2Gcmax and Barren-1 can be almost the same. For simulation purposes, it should be constructive to compare Control to the other three experiments and evaluate the mechanisms causing hydroclimate shifts between them. The simulation setup and consecutive change of land use parameter are summarized in Table 1. In Barren-1 and Barren-2, albedos over the island increase, but surface emissivity and roughness decrease because of decreasing forest area. In 0.2Gcmax, only maximum stomatal conductance has changed from Control.

3. Results and discussion

a. Comparison with the observation

Characteristics of the diurnal cycle of precipitation in the Southeast Asia region have been investigated previously, and it was found that there are distinct peaks of the diurnal cycle at specific times of the day for each location in the Southeast Asian tropics (Oki and Mushiake 1994; Ohsawa et al. 2001; Ichikawa and Yasunari 2006; Kumagai and Kume 2012; Hara et al. 2009; Kanamori et al. 2013; Bhatt et al. 2016; Fujita et al. 2010; Takahashi et al. 2010; Kodama et al. 2015). TRMM measurements revealed climatological diurnal cycles around the Maritime Continent (Nesbitt and Zipser 2003; Kikuchi and Wang 2008; Biasutti et al. 2012). Overall, the diurnal cycle of precipitation over the ocean features a low amplitude and an early morning peak, with a high amplitude and an afternoon peak over the land.

Figure 2 shows monthly averaged diurnal variations in observed precipitation $P_{\rm hr-obs}$, constructed using TRMM 3B42 data, and simulated precipitation in the numerical experiment Control $P_{\rm hr-cal}$ in the three analyzed regions: inland, coastal land, and coastal sea. The $P_{\rm hr-obs}$ was consistent with the climatological diurnal cycles around

TABLE 1. Summarized table of simulation design and consecutive parameter change in the land. The magnitude of the change of albedo, surface emissivity, and roughness due to the land use change are indicated. The + sign indicates positive, and - indicates negative. The number of signs indicates the magnitude of the change.

	Control	Barren-1	Barren-2	0.2Gcmax
Land use	USGS land use (default land use data of WRF v3.5.1)	Land use lower than 100 m MSL changed into bare land	Land use all over the island changed into bare land	Maximum stomatal conductance is 0.2 times of the original value all over the island
Albedo		+	+ +	No change
Surface emissivity		-		No change
Roughness		_		No change

the Maritime Continent. Also, our results were consistent with previous studies on Borneo (Hara et al. 2009; Kanamori et al. 2013), in which remarkable phase propagation toward inland areas occurs from noon to evening in correspondence with the distance of the observation sites from the coast. The analyses of Hara et al. (2009) implied that sea breeze fronts that form in the coastal area in the afternoon migrate to the inland area in the evening, remain even after sunset, and converge in the mid-inland area before midnight, resulting in a precipitation peak from the evening to midnight in the inland area.

It was found that the P_{hr-cal} captured the canonical form of the $P_{\text{hr-obs}}$ in the three analyzed regions (Fig. 2). Kanamori et al. (2013) suggested that in western Borneo, the precipitation amount from TRMM 3B42 tends to be overestimated (underestimated) in coastal (interior) areas as compared with in situ data. Thus, given TRMM's tendency, the discrepancies between the P_{hr-cal} and the P_{hr-obs} in inland (overestimation at midnight) and coastal land and coastal sea areas (underestimations in the afternoon and the early morning, respectively) could be neglected. Here, it should be noted that the model successfully reproduced the midnight, afternoon, and early morning peaks of precipitation in the inland, coastal land, and coastal sea areas, respectively. Also note that those peaks are generated by the offshore-inland propagation of convection [cf. discussions on offshore convection in Houze et al. (1981)], which the higher-resolution and nonhydrostatic model without cumulus parameterization allowed us to reproduce (see Hara et al. 2009; Bhatt et al. 2016). Outputs from the model were independently validated using TRMM datasets; therefore, we confirmed that the model could be used to explore the detailed physical mechanisms and feedback regarding how the LULCC over Borneo impacts the local climate, as described next.

b. Impact of the LULCC: Land surface processes

The LULCC must lead to an alteration of the energy balance on the land surface, which affects the generation of clouds and precipitation through the development of an atmospheric boundary layer (ABL; see Bonan 2008). How available energy on the land surface is partitioned into latent and sensible heat fluxes is critical to changes in the ABL height and the moistening of the lower atmosphere (see Siqueira et al. 2009). In comparison with the latent heat flux (LHF) in the Control, LHFs were reduced over the island in 0.2Gcmax and Barren-2 and only in the lowland areas in Barren-1 (Fig. 3). We found that the LHF in the deforested areas in Barren-1 and Barren-2 decreased to \sim 40% of the LHF in the Control. Total evapotranspiration over the island in the simulated month was estimated to be 115, 85, 88, and 44 mm



FIG. 2. Monthly averaged diurnal variation in precipitation from TRMM 3B42v7 datasets (solid circles) and simulated in the numerical experiment Control (lines) in the analyzed regions: inland, coastal land, and coastal sea (see Fig. 1c).



FIG. 3. Monthly mean LHF for the (a) Control, (b) 0.2Gcmax, (d) Barren-1, and (f) Barren-2 and the difference in LHF (ΔLHF) between each experiment [(c) 0.2Gcmax, (e) Barren-1, and (g) Barren-2] and the Control.

in the Control, 0.2Gcmax, Barren-1, and Barren-2 experiments, respectively.

In 0.2Gcmax, the reduction of the LHF significantly enhanced the sensible heat flux (SHF) over the island because with the unchanged surface albedo in the "green" areas, the available energy on the land surface was little changed (Figs. 4b,c). Meanwhile, despite decreases in the LHF, the SHF in both Barren-1 and Barren-2 appreciably decreased in the coastal areas, due to the higher albedo and the lower surface roughness z_0 in the deforested areas (Figs. 4d–g). In the higher-elevation areas (>100 m MSL) of Barren-1, in which forested areas



FIG. 4. As in Fig. 3, but for SHF.

with unchanged albedo and z_0 still remain and the LHF is unchanged (see Fig. 3e), the SHF was not altered (Fig. 4e). Notably, it is found that the SHFs in both Barren-1 and Barren-2 increased in the deforested inland areas (Fig. 4e,g), probably because the reduction in the partition of the available energy to the LHF and the lower z_0 increased the surface temperature. The monthly mean horizontal water vapor flux \mathbf{Q}_f integrated from the ground surface to a pressure level of 100 hPa was calculated at 1200, 1800, 0000, and 0600 LT (Fig. 5). Divergence Q_{div} of the mean \mathbf{Q}_f for the Control showed the following. At 1200 LT (Fig. 5a), the control simulation shows apparent land breeze anomalies and the occurrence of resultant positive and



FIG. 5. Monthly averaged time variations at (a)–(d) 1200, (e)–(h)1800, (i)–(l) 0000, and (m)–(p) 0600 LT in the divergence Q_{div} of the horizontal water vapor flux \mathbf{Q}_f integrated vertically from the ground surface to 100 hPa for the (first column) Control, and the difference in the Q_{div} (ΔQ_{div}) between each experiment [(second column) 0.2Gcmax, (third column) Barren-1, and (fourth column) Barren-2] and the Control. To highlight the contrast, Q_{div} and \mathbf{Q}_f vectors in the Control are represented as differences between each LT calculation and the daily mean of the Control. Arrows denote differences in the \mathbf{Q}_f between each experiment and the Control.

negative Q_{div} anomalies in the coastal sea and the coastal land regions, respectively. This might cause little precipitation around 1200 LT over the island

(Fig. 2). At 1800 LT (Fig. 5e), prominent sea breeze anomalies and the strong convergence anomalies of \mathbf{Q}_f appeared, leading to large amounts of precipitation in the coastal land and the inland regions (Fig. 2). At 0000 LT (Fig. 5i), there was likely a sea breeze, resulting in the convergence of \mathbf{Q}_f and precipitation (see Fig. 2) in the inland region. At 0600 LT (Fig. 5m), there were land breeze anomalies over the coastal zone of the island, leading to positive Q_{div} and little precipitation over the island.

Figure 5 also shows the differences in Q_{div} between each experiment and the Control: at 1200 LT (Figs. 5b-d), in Barren-1 and Barren-2, Q_{div} was strengthened in the coastal land region. At 1800 LT (Figs. 5f-h), in all the cases, Q_{div} tended to be stronger over the island. In 0.2Gcmax (Fig. 5f), there was some convergence of \mathbf{Q}_f in the inland region because of the furtherstrengthened sea breeze. In Barren-2 (Fig. 5h), we found very large land breeze anomalies and the resultant strong Q_{div} over the island. At 0000 LT (Figs. 5j–1) in 0.2Gcmax (Fig. 5j), there was a strong sea breeze and, apparently, strengthened convergence of \mathbf{Q}_f in the inland region, while stronger Q_{div} was found in Barren-1 and, especially, Barren-2 (Figs. 5k,l). At 0600 LT (Figs. 5n-p), we could detect the enhanced sea breeze and convergence-like \mathbf{Q}_f over the island in Barren-2 (Fig. 5p).

The monthly averaged Q_{div} values for the Control, 0.2Gcmax, Barren-1, and Barren-2 simulations are summarized in Fig. 6. The enhanced convergence, mainly due to the drastic increase in the \mathbf{Q}_f into the inland areas at midnight (cf. Fig. 5j), appeared over the inland region in 0.2Gcmax (Fig. 6c). By contrast, Q_{div} in Barren-1 was somewhat neutral (Fig. 6e), and Q_{div} in Barren-2 became positive over a large area of the island (Fig. 6g), mainly because of the enhanced Q_{div} in the afternoon (cf. Fig. 5h).

Local convection conditions can be represented using the convective available potential energy (CAPE), which is calculated by accumulating buoyant energy from the level of free convection to the limit of convection (see Yin et al. 2014). The monthly mean CAPE values at 1200, 1800, 0000, and 0600 LT were simulated, considering the adiabatic lifting of an air parcel from a pressure height of 850 hPa (Fig. 7). Unlike CAPE in the simulation of Swann et al. (2015) (\sim 2000–3500 J kg⁻¹), the CAPE in this study was at most $\sim 1000 \, \text{J kg}^{-1}$, comparable to Yin et al.'s (2014) observation. This suggests that changes in the CAPE induced by land surface process changes certainly affect the convective state and precipitation regime (Swann et al. 2015). The simulation results were as follows: in the Control, there were areas with large CAPE values in the inland region in the afternoon and evening (Figs. 7a,e), and, as expected, values of the CAPE were small over the island from the nighttime to the morning (Figs. 7i,m). In 0.2Gcmax (Figs. 7b,f,j,n), the CAPE increased over the island, especially at 1800 LT, except for the mountainous areas, where the CAPE was intrinsically high. In Barren-1 (Figs. 7c,g,k,o) and, more markedly, in Barren-2 (Figs. 7d, h,l,p), the CAPE decreased overall. The reduction was drastic in the coastal areas and from the evening to the nighttime for Barren-1 (Figs. 7g,k) and from the afternoon to the nighttime for Barren-2 (Figs. 7d,h,l). It is interesting to note that in the three numerical experiments, the increase/decrease in the CAPE corresponded to those in specific humidity at a height of 850 hPa and in cloud water around a height of 800 hPa (data not shown here), implying a decrease/increase in the lifting condensation level (LCL). The impact of the LULCC on precipitation regimes can be explained by a combination of the evolution of the ABL induced by the available radiative energy partitioning, the CAPE change, and the LCL change (see Siqueira et al. 2009), as discussed next.

c. Impact of the LULCC: Precipitation

Figure 8 compares the diurnal cycles of the precipitation simulated in the numerical experiments. Again, in the Control, the diurnal cycles of precipitation were well reproduced over the island (see Fig. 2). In 0.2Gcmax, the precipitation increased mainly in the inland region from the night (2000 LT) to the morning (0800 LT; Fig. 8), which can be partly attributed to some convergence of \mathbf{Q}_f (Figs. 5f,j,n) and enhanced cloud development caused by the increase in the CAPE (Fig. 7f, j) around the time. It is interesting to note that deforestation in the lowland area (Barren-1 in Fig. 8), which is almost equivalent to that in the coastal land area, appreciably reduced the precipitation in not only the coastal land region (from the afternoon through the evening) but also in the inland region (from the evening through the early morning), echoing the conclusions of Lawton et al. (2001), who demonstrated that changes in clouds over mountainous areas result from deforestation in nearby lowland areas. This decrease in precipitation in the inland region in Barren-1 might be caused by the depressed CAPE in the inland region around midnight (Fig. 7k). In Barren-2 (Fig. 8), the precipitation was further reduced in the inland area (from the afternoon through midnight) and in the coastal land area (mainly in the afternoon), due to the drastic divergence of \mathbf{Q}_{f} (Figs. 5h,l) and the depressed CAPE (Figs. 7d,h) around that time. A reduction in the precipitation in the coastal sea area can be seen only in the morning in Barren-2 (Fig. 8). Note that the LULCC over Borneo causes an increase (in 0.2Gcmax) and/or a decrease (in Barren-1 and Barren-2) in the amplitude of the precipitation diurnal cycle. This suggests that the changes in the land surface heating process (see Dai 2001) from the LULCC would reinforce or weaken the land-sea breeze circulation in the studied area, that is, the night precipitation



FIG. 6. As in Fig. 3, but for Q_{div} . Arrows in (c), (e), and (g) denote differences in \mathbf{Q}_f between each experiment and the Control.

peak in the inland region, the afternoon peak in the coastal land area, and the morning peak in the coastal sea area (see Ichikawa and Yasunari 2006; Teo et al. 2011; Kanamori et al. 2013).

The spatial distribution of the monthly accumulated precipitation P_{mon} in each numerical experiment and

the differences in P_{mon} between each numerical experiment and the Control are shown in Fig. 9. In the simulation that assumed a change in the gas exchange traits of the forest canopy, that is, 0.2Gcmax (Figs. 9b,c), P_{mon} increased as compared to the Control, mainly because of an increase in the precipitation in the inland region and



FIG. 7. As in Fig. 5, but for the CAPE calculated considering the adiabatic lifting of an air parcel from 850 hPa.

from the night to the morning (see Fig. 8). In the simulations assuming two deforestation patterns, that is, Barren-1 and Barren-2 (Figs. 9d–g), P_{mon} apparently decreased over the island, despite small areas with increases in the P_{mon} . This decrease could be caused by the reduction of precipitation in the inland and coastal

inland regions and from the afternoon to the early morning (see Fig. 8).

Finally, the cause and effects of the precipitation changes induced by the LULCC are summarized in Fig. 10, where all of the variables (i.e., evapotranspiration E, precipitation P, CAPE, horizontal water vapor



FIG. 8. As in Fig. 2, but for the precipitation simulated in the numerical experiments of the Control, 0.2Gcmax, Barren-1, and Barren-2.

flux Q_{div} , horizontal wind velocity U, albedo, and SHF) were integrated over Borneo in the studied month. Parameters Q_{div} and U were calculated as radius components of the polar coordinates whose center is located at the center of Borneo, and their positive values represent quantities directed from the center to the outside of the island. Again, as compared to the Control, P increased by 8.5% in 0.2Gcmax, while P decreased by 16% and 43% in Barren-1 and Barren-2, respectively (Fig. 10).

As imposed preconditions, the reduction of E was the same in 0.2Gcmax and Barren-1, and E in Barren-2 was more than twofold the E of 0.2Gcmax and Barren-1 (Fig. 10a). On the other hand, convergence of the air mass flow and resulting convergence of Q_{div} (negative values of U and Q_{div}) were found in 0.2Gcmax. In Barren-1 and Barren-2, outflow of air mass and Q_{div} from the island occurred. Here, it is important to note that in all of the numerical experiments, the quantities of P change cannot be explained by only the quantities of the local E changes, and the Q_{div} in the objective area must play a key role when considering how much P increases or decreases there (cf. Spracklen et al. 2012).

In 0.2Gcmax, no change in the albedo and the decrease in E (latent heat) lead to the least change in land surface available energy and a significant increase in the SHF (Figs. 10a,b). In Barren-1 and Barren-2, the albedo increased appreciably, and thus, the available energy was reduced. As the *E* was also reduced, SHF changed little in Barren-1 and Barren-2. The larger SHF should develop a higher ABL in 0.2Gcmax than in Barren-1. Despite the same reduction in *E* for both experiments, there was an inflow of Q_{div} over the island, the atmosphere below the ABL was more moistened, and the height of the LCL decreased in 0.2Gcmax. Thus, 0.2Gcmax would produce more favorable conditions for a convective precipitation trigger (cf. Siqueira et al. 2009).

Furthermore, the larger increase in SHF led to an increase in CAPE in 0.2Gcmax, and in Barren-1 and Barren-2, the smaller increase in SHF could not compensate for the effect of the reduction of atmospheric moisture, leading to a decrease in CAPE (Fig. 10). In general, an increase in CAPE results in an increase in P (e.g., Swann et al. 2015). In addition to this, the enhanced CAPE in an inland area of the island should reinforce Q_{div} from the sea to the inland region (see Fu et al. 1999), resulting in further increments of P.

4. Conclusions and implications

Previous analysis explored the vulnerability of the local hydroclimate to deforestation and forest degradation on Borneo (Kumagai et al. 2013). To quantify how the LULCC affects the land surface processes, the surfaceinduced mesoscale circulation, the atmospheric interaction between land and sea, and the resulting regional precipitation over the island, we used the WRF Model with an appropriate land surface model to describe the influence of changes in vegetation status on the atmosphere (Noah LSM; Mitchell 2005). Since the diurnal cycle of precipitation is a dominant feature of the atmospheric water cycle over the Maritime Continent (Ichikawa and Yasunari 2006; Kanamori et al. 2013), the model's ability to reproduce such a precipitation regime is crucial to the present study's investigation (Hara et al. 2009; Bhatt et al. 2016). In this study, employing higherresolution grid spacing, an appropriate convective parameterization scheme, and a cloud microphysical process scheme in the model enabled us to successfully reproduce the observed precipitation characteristics over the island of Borneo. After validating the model, we proceeded to numerical experiments to clarify the impact of the LULCC on the precipitation regimens over the island, demonstrating the following:

 Deforestation that generates bare land or areas with high albedo would induce a reduction in precipitation. Deforestation directly decreases forest evapotranspiration, and the albedo increment accompanied by deforestation restricts convection and horizontal atmospheric moisture inflow through



FIG. 9. As in Fig. 3, but for P_{mon} .

the effects of depressed available radiative energy and sensible heat flux. This results in a decreased water supply to the local atmosphere, and, thus, reduced precipitation on the island.

 On the other hand, a decrease in evapotranspiration efficiency, that is, canopy conductance, possibly caused by a change in the vegetation type, without changing the surface albedo could increase precipitation. An increase in sensible heat flux due to the minimal change in available energy and a decrease in the latent heat flux would produce active convection and draw the horizontal atmospheric moisture flow, compensating for the decreased moisture supply to the atmosphere by evapotranspiration. This possibly



FIG. 10. Differences in evapotranspiration dE, precipitation dP, sensible heat flux dSHF, horizontal wind velocity dU, horizontal water vapor flux dQ_{div} , and convective available potential energy dCAPE between each experiment (0.2Gcmax, Barren-1, and Barren-2) and Control. The dCAPE, dQ_{div} , and dU were simulated at 850 hPa. (a) Direct effect due to the simulation setup, that is, dE, dP, dSHF. (b) Effect of feedback processes, that is dU, dQ_{div} , and dCAPE. The error bars indicate standard errors calculated from the day-to-day variability.

leads to an increase in precipitation on the island, despite the decrease in evapotranspiration.

3) In the Maritime Continent, through changes in the land surface heating process and land-sea breeze circulation, the LULCC would impact the amplitude of the diurnal precipitation cycle in each region on the island, defined according to the distance from the coast. Also, the changes should be propagated in the precipitation regimes from the coastal to the inland regions: deforestation only in the lowland and coastal areas would affect the precipitation regimes in the mountainous and inland areas.

In practice, these findings might imply that the impact of the LULCC on the local hydroclimate on Borneo is highly uncertain. In particular, in the case of Southeast Asian tropical forests, deforestation does not necessarily mean fully bare lands, and the land surface properties of the secondary vegetation, such as evapotranspiration and surface albedo, quickly resemble those of the original forest again (Giambelluca et al. 1999; Giambelluca 2002). Also, the evapotranspiration of the plantation developed after deforestation cannot be declared appreciably changed from that of the original tropical forest (e.g., Giambelluca et al. 2016). Therefore, the next step for the present study should be simulations utilizing more realistic future deforestation scenarios for Borneo (cf. Gaveau et al. 2014).

With global implications, sea surface temperature (SST) forcing should be taken into account because of the SST's pervasive influence on the mean simulated climate (see Voldoire and Royer 2004). Impacts of the LULCC on the local hydroclimate could pose a considerable risk to agricultural productivity and forest dynamics downstream of the LULCC (see Spracklen et al. 2012; Lawrence and Vandecar 2014). On a smaller scale, in this study, a significant decrease in precipitation was found in the forested mountainous area

adjacent to the deforested lowland area. This could lead to changes in forest dynamics, for example, high rate of mortality, in such a transitional zone, in turn, causing feedback to the atmosphere (see Delire et al. 2004; Wang et al. 2011).

As Mahmood et al. (2016) pointed out, despite the recognition of both LULCC-driven biogeochemical (e.g., enhanced carbon emissions) and biogeophysical (e.g., changed water cycle and surface energy fluxes) impacts on the climate system by the scientific community, international protocols on the mitigation of LULCC-driven climate change do little to address the biogeophysical impact: most protocols only focus on the reduction of carbon emissions. Thus, to bring the biogeophysical impact to the attention of policy-makers and the general public, we need to provide information derived from more mechanistic and quantitative assessments. Although there still remains a lack of realistic understanding of the LULCC-driven impact on Borneo's local climate, we believe that the outcomes and findings of the present analysis could be the first step and could be attractive starting points for more extensive and technically difficult experiments.

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