Impact of land-cover change between 1990 and 2000 on the regional climate of Paraguay: a first overview

Alicia Pavetti Infanzón, Kenji Tanaka and Shigenobu Tanaka
Disaster Prevention Research Institute, Kyoto University, Japan

Abstract:

Land-use change poses a major threat over much of the La Plata River Basin in South America. Paraguay, with one of the highest deforestation rates in the region, has experienced rapid loss of its natural forests. Such landscape transformation implies changes in vegetation traits that affect exchange of momentum, heat, and moisture between the surface and atmosphere. To understand how the regional climate of Paraguay could be affected by the deforestation that occurred between 1990 and 2000, we ran 1-month long simulations for each November during the 2006–2012 period for a control scenario and a past vegetation scenario. Climate responses to land-cover change differed with location and vegetation. In eastern Paraguay, replacement of forest with farmland increased albedo, leading to an overall lower latent heat and both lower and higher sensible heat fluxes. In western Paraguay, replacement of grassland with farmland slightly increased albedo, reducing the sensible heat and increasing evapotranspiration owing to greater surface soil wetness. Effects of land-use change on precipitation are more likely to change local patterns of precipitation than they are the country’s total monthly precipitation.

KEYWORDS land-cover change; regional climate; modeling; Paraguay

INTRODUCTION

Climate is influenced not only by the behavior of atmospheric variables, but also by soil and vegetation dynamics (Pielke, 2001; Mahmood et al., 2013, 2016). Changes in land cover imply changes in the biophysical properties of the surface, such as albedo, leaf area, roughness length, root depth, stomatal resistance, and other properties that depend on the land-cover type. Changes in vegetation traits can affect the exchange of momentum, heat, and moisture between the atmosphere and the underlying surface, and thus influence climate at different spatial and temporal scales (Pielke and Avisser, 1990; Pielke et al., 2007b; Mahmood et al., 2013; Pielke et al., 2016). Although these effects may go unnoticed in the global average, they can be significant at regional scales because they directly affect the patterns of rainfall and temperature as well as air circulation processes (Pielke, 2001; Werth and Avisser, 2002; Silva Dias, 2006; Mahmood et al., 2013; Pielke et al., 2016).

The results of several studies in the Amazon region of the regional effects of land-cover change associate deforestation of tropical forests with reductions in evapotranspiration and moisture fluxes and, consequently, precipitation by altering its intensity and spatial patterns (Nobre et al., 1991; Hahmann and Dickinson, 1997; Baidya Roy and Avisser, 2002; Werth and Avisser, 2002). However, only a few studies have addressed the topic in southern South America, where extensive land-use change has occurred in recent decades: Beltrán-Przekurat et al. (2012) performed a series of regional numerical simulations to evaluate the potential effects of land-use change on the near-surface atmosphere at the seasonal scale. Lee and Berbery (2012) carried out multiple 3-month numerical experiments using the atmosphere-land coupled WRF-Noah model to assess the potential regional impacts of land-cover change in the La Plata River Basin on precipitation and near-surface temperature during spring. Both of these studies, however, were aimed at performing sensitivity experiments by assuming idealized or potential future land-use scenarios. Lee et al. (2013) further explored the impacts of land-cover change on the climate of the La Plata River Basin during the springtime by studying the sensitivity of air temperature and precipitation to ecosystem functional type differences between 1988 and 1998. However, to the best of our knowledge, multi-year ensembles simulations that consider real land-cover change have not yet been assessed in the region, in particular in Paraguay, a country highly affected by the rapid expansion of the agricultural frontier and which has lost over 75% of its Atlantic forest over the last several decades with massive loss of forest resources since the early 1970s (Cartes, 2003; Huang et al., 2007, 2009).

To investigate how actual land-cover change might affect the regional climate of Paraguay, we ran two sets of 1-month long simulations for each November during the 2006–2012 period using the same atmospheric boundary conditions but different vegetation scenarios. The main objective was to assess how local changes in vegetation could drive changes in the precipitation and temperature patterns of Paraguay and understand the mechanisms involved in such processes.
A. PAVETTI INFANZÓN ET AL.

METHODS

Model configuration and simulations settings

We used the meso-scale numerical weather prediction model CReSiBUC (Moteki et al., 2005) to run simulations with different land-use scenarios to investigate how the forest loss experienced in Paraguay between 1990 and 2000 could affect local and regional climate during the month of November. CReSiBUC is an atmosphere-land coupled model composed of the Cloud Resolving Storm Simulator (CReSS) and the Simple Biosphere model including Urban Canopy (SiBUC). CReSS is a non-hydrostatic compressible model capable of simulating cloud and precipitation systems (Tsuboki and Sakakibara, 2007). SiBUC is a land surface model that calculates surface fluxes and meteorological variables through the consideration of detailed processes (Tanaka, 2004). CReSiBUC has been used to study the effects of artificial land cover on rainfall (Ikebuchi et al., 2007; Fujii et al., 2011; Souma et al., 2013a, 2013b).

SiBUC calculates radiation, heat, mass transfer, and momentum budgets for different values of surface condition parameters. It relies on three main submodels of green areas, urban areas, and water bodies. The green area submodel is based on the Simple Biosphere model (Sellers et al., 1986), which models the morphological and physiological characteristics of the vegetation community at each grid point in order to calculate the coefficients and resistances that govern fluxes between the surface and the atmosphere. SiBUC takes a mosaic approach to land heterogeneity, which allows the incorporation of several land-use categories within the grid element, and thus independently couples each land-use patch to the atmosphere by returning grid-averaged surface fluxes to CReSS (i.e. average of surface fluxes over each land use weighted by its fractional area).

CReSiBUC is integrated at a regional scale over a nested domain (5-km horizontal grid spacing) within a mother domain (20-km horizontal grid spacing) centered at 23.5°S, 58°W (Figure 1). The vertical grid is composed of 50 levels with an average spacing of 500 m, using a cubic function for vertical stretching. The ground and sea components each have 30 layers with a thickness of 0.1 and 0.4 m, respectively. The model uses cloud microphysics of bulk cold rain parameterization that solves the tendency equation of number densities of ice phase hydrometeors.

We ran simulations of land-use change in Paraguay to assess how modifications in the surface characteristics and traits could affect precipitation, temperature, and the processes that govern the regional climate. The simulations covered a 1-month long period from 1 to 30 of all Novembers during the years 2006–2012. November is also the planting season of soybean, which is one of Paraguay’s main agricultural commodities, and falls in the middle of the period of highest precipitation rates in the country, thus the land-atmosphere interactions are expected to become large. Initial fields and atmospheric boundary conditions for the mother domain were acquired from the Japanese Re-Analysis dataset (Ebita et al., 2011), with an interval of 6 h and a horizontal spacing of 1.25°. The fields for the nested domain were obtained from the outcomes of the mother domain simulations at an interval of 6 h and a horizontal grid spacing of 20 km (see Table I). Externally forced parameters comprised the z-coordinate, horizontal velocity components, pressure, potential temperature, and water vapor mixing ratio. Since the mother domain covers ocean areas, the lower boundary condition also considered sea surface temperatures. The dataset used for this study was the Group for High Resolution Sea Surface Temperature’s Multi-scale Ultra-high Resolution Sea Surface Temperatures set, obtained from the NASA Earth Observing System Data and Information System’s Physical Oceanography Distributed Active Center, which is a high-resolution combined sea surface temperature and sea ice analysis system that has a global resolution of 0.05° (~ 6 km) and daily temporal resolution (UK Met Office, 2005).

Soil physical parameters were prescribed following the ECOCLIMAP product at 1-km resolution (Chameaux et al., 2005). In CReSiBUC, simulations run in time spans of 10 days, and the initial soil condition for the start of any period is obtained from the previous 10 days’ simulation. In our simulations, however, which began on 1 November each year, soil moisture started from an assumed initial wet value. Although Rodell et al. (2005) suggest that there are better techniques for initializing land surface models than simply considering a dry or wet initialization, as spin-up times are controlled by the variables of freezing temperatures and precipitation, humid regions such as subtropical South America reach hydrological equilibrium quickly.

Design of land-cover change simulations

To isolate the effects of land-cover change over Paraguay, we ran two sets of simulations for 1 to 30 of each November during the 2006–2012 period (Table I). The first set used the vegetation distribution in 2000, which we considered the modified state of land cover, and thus used it as the Control set. The vegetation scenario for the Control simulations were obtained by combining the United State Geological Survey (USGS) Global Land Cover Characterization data (Figure 2a) and the Paraguay Forest Change product (PFC), which was derived by the Global Land Cover Facility (2006) from Landsat TM and TM+ imagery at a spatial resolution of 28.5 m (Figure 2b). The PFC contains the distribution of forested and unforested areas in

Figure 1. Study region: mother domain (whole image) and nested domain (bounded in red)
Table I. CreSiBUC simulation settings for CONTROL and PAST simulations

| Simulation set | CONTROL | PAST |
|----------------|---------|------|
| integration time (hours) | Nov 2006–2012 (5040) | Nov 2006–2012 (5040) |
| No. of Points (xdim, ydim, zdim) | 240, 144, 50 | 240, 144, 50 |
| Horizontal Grid (m) (xspacing, yspacing) | 20000, 20000 | 20000, 20000 |
| Atmos. Conditions (intvl., spacing) | JRA (6 hours, 1.25°) | JRA (6 hours, 1.25°) |
| land use | Year 2000 | Year 1990 |
| NDVI | AVHRR (avg. 1991–2000) | AVHRR (avg. 1981–1990) |
| Surface Process | w/SiBUC | w/SiBUC |

AVHRR = Advanced Very High Resolution Radiometer; CRS = CreSiBUC; JRA = Japanese Re-Analysis (Ebita et al., 2011); SiBUC = Simple Biosphere model including Urban Canopy.

Paraguay in 2000 (labeled as Atlantic Forest, Chaco woodland, Non-forest, and Water), as well as the locations where deforestation occurred between 1990 and 2000 (Atlantic Forest Loss and Chaco Woodland Loss). To match the USGS data, the PFC was scaled up to a 1-km resolution by adopting the predominant land use type within each 1-km × 1-km pixel. The datasets were then combined by replacing the USGS vegetation types with the information from the PFC for 2000 within Paraguay and re-categorizing it following the USGS classification system, on which the SiBUC’s green area submodel is based. Land-use types labeled by the PFC product as Atlantic Forest Loss, Chaco Woodland Loss, and Non-Forest were categorized as Farmland, and Atlantic Forest and Chaco Woodland were converted into Forest and Grassland, respectively (Figure 2d).

To reveal the effects of the actual land-use change in Paraguay between 1990 and 2000, we also ran a set of Past simulations. These simulations assumed a vegetation scenario that represented the land-cover patterns in 1990. As in the Control simulations, USGS data were combined with the PFC product, but land-use types labeled as Atlantic Forest Loss and Chaco Woodland Loss were converted into Forest and Grassland, respectively (Figure 2c).

The performance of CreSiBUC was evaluated with respect to precipitation and temperature (see Text S1). The significance of average differences in albedo, sensible and latent heat fluxes, temperatures, and precipitation between Control and Past scenario runs was evaluated by t-test in each grid element.

Land-cover changes are accompanied by changes in normalized difference vegetation index (NDVI) and other physical properties such as albedo, surface roughness length, emissivity, root depth, and stomatal resistance that depend on the land cover type. NDVI data were adjusted to the specifications of each vegetation scenario. For this purpose, the 8-km-resolution Advanced Very High Resolution Radiometer NDVI (Tucker et al., 2005) was pre-processed to reduce bias in the data (see Pavetti Infanzón, 2014), and November means of NDVI values for every 8-km × 8-km pixel were calculated for the periods 1991–2000 (Control simulations) and 1981–1990 (Past simulations). The use of averaged values (i.e. NDVI average for 1981–1990 and 1991–2000; Figure S4) instead of single-year values (i.e. NDVI values for 1990 and 2000 only) reduced the influence of interannual variability in NDVI and represented more accurately the changes in the patterns of NDVI due to the land-use change that occurred in the period under study.

RESULTS AND DISCUSSION

Surface heat fluxes and surface energy balance

Land cover change in Paraguay between 1990 and 2000...
had, for the most part, different effects on surface heat flux and the energy balance depending on the location and the replacement vegetation. Albedo (upward shortwave radiation) was higher in the Control simulations, particularly in eastern Paraguay, where forests were replaced by farmlands (Figure 3b). The pattern of albedo change resembled that of NDVI (Figure S4) and was congruent with the vegetation changes that were assumed in these simulations (Figure 2).

In the Control simulations, the sensible heat flux was larger in mountainous areas and smaller over wetter, low-altitude regions, while latent heat flux (which is related to evapotranspiration) showed the opposite behavior (Figure 3c, e). The differences between Control and Past simulations showed widespread changes, but generally, in areas where the latent heat flux decreased, the sensible heat increased and vice versa, although changes also depended on location (Figure 3d, f). For instance, the forested areas that were replaced by farmlands in eastern Paraguay experienced a combination of slight increases and decreases in the sensible heat flux and a decrease in the latent heat flux, in agreement with reports that evaporation is greater in forests than in pastures, grass, and crops (Dickinson and Henderson-Sellers, 1988; Lean and Warrilow, 1989; Nobre et al., 1991; Werth and Avissar, 2002; Mahmood et al., 2013). In western Paraguay, in contrast, the shift of grasslands to farmlands matched a decrease in sensible heat and an increase in evapotranspiration due to greater surface soil wetness (Figure S5).

To further understand the implications of vegetation replacement at the local scale, we also analyzed the mean diurnal cycle of surface energy balance over regions where forests and grasslands were converted to farmland. The total net radiation over forests was composed mainly of latent heat flux and partly of sensible heat flux (Figure 4a). Since large changes in vegetation traits occur when forests are replaced by farmland, effects on the energy budget are expected to be noticeable. Modifications in albedo have a direct impact on the total available energy, because they alter the capacity of the surface to absorb incoming solar radiation; i.e. increased albedo (decreased surface absorption) leads to decreases in the energy budget and vice versa. The differences between Control and Past simulations (Figure 4b, Table SI) indicate a reduction in net radiation as a result of higher albedo in the Control simulation (Figure 3b), composed of decreases in both latent and sensible heat fluxes. Lee and Berbery (2012) reported similar results in their study of the La Plata River Basin, with the exception of increments in latent heat flux that they attributed to nonlocal effects. As in forests, grasslands in western Paraguay had a similar energy balance, albeit with lower net radiation and a higher relative contribution of latent heat flux (Figure 4c). The vegetation changes in this region resulted in a small decrease in net radiation (Figure 4c, d, Table SI) that is consistent with the slight increase in albedo (Figure 3b), an increase in latent heat flux, and a large decrease in sensible heat flux.

---

Figure 3. 2006–2012 November averages of (a, c, e) Control experiment and (b, d, f) Control – Past differences in (a, b) upward shortwave radiation (W m⁻²), (c, d) sensible heat flux (W m⁻²), and (e, f) latent heat flux (W m⁻²). Adjacent patches that differ at P < 0.05 are separated by a thin black line.

Figure 4. (a, c) Mean diurnal cycles of surface flux (W m⁻²) and (b, d) differences between Control and Past at (a, b) 55.64°W, 25.88°S (forest → farmland) and (c, d) 60.09°W, 21.99°S (grassland → farmland).
Near-surface temperature and precipitation

Changes in surface fluxes led to changes in mean air temperature and daily temperature range (Figure 5b, d). Overall, the 0.3°C warming of the near-surface atmosphere corresponded with the increase in sensible heat flux (Figure 3d), although this warming was not statistically significant. The reduction of latent heat flux in some areas of eastern Paraguay (Figure 3f) increased the heating capacity of the atmosphere, which caused a gradual decrease in nighttime temperatures that were associated with higher daily minimum temperatures (Figure S6). In the same way, the reduction in sensible heat in other regions was related to lower daytime maximum temperatures that led to an overall reduction in the local daily temperature range (Figure 5d). In western Paraguay, the same principles explain the wider temperature range, which corresponded with warmer daily maximum and cooler daily minimum temperatures.

Changes in land cover are accompanied by changes in the biophysical properties of the surface that depend on the type of vegetation. In particular, albedo and roughness length are well known for their influence on the surface energy balance and wind, affecting not only the amount of precipitation but also its spatial distribution at the local scale (Pielke and Avisser, 1990; Pielke, 2001; Pielke et al., 2007a; Pielke et al., 2007b; Werth and Avisser, 2002; Silva Dias, 2006; Mahmood et al., 2013; Pielke et al., 2016). The replacement of forests and grasslands by farmlands caused an overall reduction of precipitation as high as 100 mm month⁻¹ in Eastern Paraguay and widespread increases and decreases of the order of 50 mm month⁻¹ in Western Paraguay (Figure 5f). As a general rule, the areas of precipitation decrease are approximately situated in areas that experienced latent heat flux reduction and increased sensible heat flux (Figure 3d, f). The changes in latent heat flux (i.e. evapotranspiration) in combination with changes in roughness length affect the moisture fluxes that can lead to changes in precipitation, although CONTROL – PAST differences were significant in only a few small areas. The total monthly precipitation over the country was the same in both Control and Past simulations, suggesting that the land-use changes between 1990 and 2000 were more likely to have significant effects on the patterns of precipitation at the local scale than on the total. These results could mean that the extent of landscape transformation assumed in the simulations was not large enough to effectively link changes in mean temperature and precipitation to changes in land cover. However, they could also mean that the soil moisture initialization might have influenced the intensity of the impacts of land-use change by preventing larger modifications of the total available energy and affecting its partition into latent and sensible heat fluxes. Beltrán-Przekurat et al. (2012) evaluated the sensitivity of land-cover change impacts to initial soil moisture in southern South America and found that wetter (drier) initial conditions tended to lessen (amplify) the response of temperature and precipitation, although for the latter, wetter conditions could also have the opposite effect depending on the region. Moreover, the aforementioned study also found that the sensitivity was not too large for the case of temperature but it could be as large as the impact of land-use change for the case of precipitation. Considering that our 1-month long simulations are rather short, which could signify a disadvantage given our initial soil moisture assumptions, the issue was partially addressed by performing multi-year simulations for the same period (i.e. 1-month simulations for each November during the years 2006–2012).

**SUMMARY**

This preliminary overview of the effects of land-cover change between 1990 and 2000 on the regional climate of Paraguay was made possible by performing two sets of simulations with the CReSiBUC model. The simulations assumed a modified vegetation distribution and a past distribution based on the PFC product. For the most part, the results were those expected given the assumptions made. Overall, the replacement of natural vegetation with farmland increased the albedo. The near-surface heat flux and surface energy balance depended on the location and the type of replacement vegetation. Differences between Control and Past simulations showed that where forests were replaced by farmland in eastern Paraguay, the effects included a reduction in latent heat flux and an increase in sensible heat flux, but where grasslands were replaced by farmland in western Paraguay, the results were the opposite. Those changes in heat flux caused warming over part...
of the country, as well as a narrower temperature range over eastern Paraguay and a wider range over western Paraguay. Land use change was more likely to produce changes in the local patterns of precipitation, and had almost no effect on the country’s monthly total. These results give important insights into the mechanisms that govern land-atmosphere interactions. However, owing to the limitations of this research, particularly the relatively short period, the initial soil moisture assumptions, and the extent of the landscape transformation considered, further simulations and analysis will be needed to obtain a better understanding.

ACKNOWLEDGMENTS

The Group for High Resolution Sea Surface Temperature’s Multi-scale Ultra-high Resolution sea surface temperature data were obtained from the NASA EOSDIS Physical Oceanography Distributed Active Archive Center at the Jet Propulsion Laboratory, Pasadena, California, USA (http://dx.doi.org/10.5067/GHGMR-4FJ01).

SUPPLEMENTS

Text S1. Evaluation of CReSiBUC model performance
Figure S1. 2006–2012 November averages of CRU observations and Control experiment in maximum and minimum temperatures
Figure S2. 2006–2012 November averages of TRMM observations and Control experiment in precipitation
Figure S3. 2006–2012 November averages over Paraguay of TRMM observations and Control experiment in daily precipitation and monthly total accumulated precipitation
Figure S4. Differences in November NDVI averages of 1991–2000 and 1981–1990
Figure S5. Control – Past differences in surface soil wetness and root zone soil wetness
Figure S6. 2006–2012 average Control values and Control – Past differences in daily maximum and minimum temperatures
Table S1. 24-hours mean surface fluxes (W m⁻²) for Control and Past experiments, and Control – Past differences at 55.64°W, 25.88°S (forest → farmland) and 60.09°W, 21.99°S (grassland → farmland)

REFERENCES

Baidya Roy S, Avisar R. 2002. Impact of land use/land cover change on regional hydrometeorology in Amazonia. Journal of Geophysical Research 107: LBA 4-1–LBA 4-12. DOI: 10.1029/2000JD000266.

Beltrán-Przekurat A, Pielke RA, Eastman JL, Coughenour MB. 2012. Modelling the effects of land-use/land-cover changes on the near-surface atmosphere in southern South America. International Journal of Climatology 32: 1206–1225. DOI: 10.1002/joc.2346.

Cartes JL. 2003. Brief history of conservation in the interior Atlantic forest. In The Atlantic Forest of South America: Biodiversity status, threats and outlook, Galindo-Leal C, Camara IG (eds). Washington, USA; 269–287.

Chameaux JL, Masson V, Chauvin F. 2005. ECOCCLIMAP: a global database of land surface parameters at 1 km resolution. Meteorological Applications 12: 29–32. DOI: 10.1017/S1350482705001519.

Dickinson RE, Henderson-Sellers A. 1988. Modelling tropical deforestation: A study of GCM land-surface parameterizations. Quarterly Journal of the Royal Meteorological Society 114: 439–462. DOI: 10.1002/qj.49711448009.

Ebita A, Kobayashi S, Ota Y, Moriya M, Kumabe R, Onogi K, Harada Y, Yasui S, Miyaoka K, Takahashi K, Kamahori H, Kobayashi C, Endo H, Soma M, Oikawa Y, Ishimizu T. 2011. The Japanese 55-year Reanalysis “JRA-55”: An Interim Report. Scientific Online Letters on the Atmosphere 7: 149–152. DOI: 10.2151 sola.2011-038.

Fujii T, Tanaka K, Souma K, Kojiri T. 2011. Physical-based downscaling including characteristics of urban weather. Journal of Japan Society of Civil Engineers 67: 355–360 (in Japanese with English abstract). DOI: 10.2208/jscejhe.67J.355.

Hahmann AN, Dickinson RE. 1997. RCCM2-BATS model over tropical South America: Applications to tropical deforestation. Journal of Climate 10: 1944–1964. DOI: 10.1175/1520-0442(1997)010<1944:RBMOSTS>2.0.CO;2.

Huang C, Kim S, Altstatt A, Townsend JRG, Davis P, Song K, Tucker CJ, Rodas O, Yanosky A, Clay R, Musinsky J. 2007. Rapid loss of Paraguay’s Atlantic forest and the status of protected areas – A Landsat assessment. Remote Sensing of Environment 106: 460–466. DOI: 10.1016/j.rse.2006.09.016.

Huang C, Kim S, Song K, Townsend JRG, Davis P, Altstatt A, Rodas O, Yanosky A, Clay R, Tucker CJ, Musinsky J. 2009. Assessment of Paraguay’s forest cover change using Landsat observations. Global and Planetary Change 67: 1–12. DOI: 10.1016/j.gloplacha.2008.12.009.

Ikebuchi S, Tanaka K, Ito Y, Moteki Q, Souma K, Yorozu K. 2007. Investigation of the effects of urban heating on the heavy rainfall event by a cloud resolving model CReSiBUC. Annuals of Disaster Prevention Research Institute, Kyoto University 50: 105–111.

Lean J, Warrillow DA. 1989. Simulation of the regional climatic impact of Amazon deforestation. Nature 342: 411–413. DOI: 10.1038/342411a0.

Lee SJ, Berbery EH. 2012. Land cover change effects on the climate of the La Plata Basin. Journal of Hydrometeorology 13: 84–102. DOI: 10.1175/JHM-D-11-021.1.

Lee SJ, Berbery EH, Alcaraz-Segura D. 2013. The impact of ecosystem functional type changes on the La Plata Basin climate. Advances in Atmospheric Sciences 30: 1387–1405. DOI: 10.1007/s00376-012-2149-x.

Mahmood R, Pielke RA, Hubbard KG, Niyogi D, Dirmeyer PA, McAlpine C, Carleton AM, Hale R, Gameda S, Beltrán-Przekurat A, Baker B, McNider R, Legates DR, Shepherd M, Du J, Blanken PD, Frauenfeld OW, Nair US, Fall S. 2013. Land cover changes and their biogeophysical effects on climate. International Journal of Climatology 34: 929–953. DOI: 10.1002/joc.3736.

Mahmood R, Pielke RA, McAlpine CA. 2016. Climate-relevant land use and land cover change policies. Bulletin of the American Meteorological Society 97: 195–202. DOI: 10.1175/BAMS-D-14-00221.1.

Moteki Q, Ito Y, Yorozu K, Souma K, Sakakibara A, Tsuboki K, Kato T, Tanaka K, Ikebuchi S. 2005. Estimation for effects of existence of urban on development of cumulonimbus
clouds using atmosphere-land coupled model of CReSiBUC. *Annuals of Disaster Prevention Research Institute, Kyoto University* **48**: 197–208.

Nobre CA, Sellers PJ, Shukla J. 1991. Amazonian deforestation and regional climate change. *Journal of Climate* **4**: 957–988. DOI: 10.1175/1520-0442(1991)004<0957:ADARCC>2.0.CO;2.

Pavetti Infanzón A. 2014. Reproduction of long-term vegetation change and its application to regional climate change study in Paraguay. *Master’s Thesis, Graduate School of Engineering, Kyoto University*, Kyoto; 19–30.

Pielke RA. 2001. Influence of the spatial distribution of vegetation and soils on the prediction of cumulus convective rainfall. *Reviews of Geophysics* **39**: 151–177. DOI: 10.1029/1999RG000072.

Pielke RA, Avissar R. 1990. Influence of landscape structure on local and regional climate. *Landscape Ecology* **4**: 133–155. DOI: 10.1007/BF00132857.

Pielke RA, Adegoke J, Beltrán-Przekurat A, Hiemstra CA, Lin J, Nair US, Niyogi D, Nobis TE. 2007a. An overview of regional land-use and land-cover impacts on rainfall. *Tellus B: Chemical and Physical Meteorology* **59**: 587–601. DOI: 10.1111/j.1600-0889.2007.00251.x.

Pielke RA, Adegoke JO, Chase TN, Marshall CH, Matsui T, Niyogi D. 2007b. A new paradigm for assessing the role of agriculture in the climate system and in climate change. *Agricultural and Forest Meteorology* **142**: 234–254. DOI: 10.1016/j.agrformet.2006.06.012.

Pielke RA, Mahmood R, McAlpine C. 2016. Land’s complex role in climate change. *Physics Today* **69**: 40–46. DOI: 10.1063/PT.3.3364.

Roddell M, Houser PR, Berg AA, Famiglietti JS. 2005. Evaluation of 10 methods for initializing a land surface model. *Journal of Hydrometeorology* **6**: 146–155. DOI: 10.1175/JHM414.1.

Sellers PJ, Mintz Y, Sud YC, Dalcher A. 1986. A Simple Biosphere Model (SiB) for use within General Circulation Models. *Journal of the Atmospheric Sciences* **43**: 505–531. DOI: 10.1175/1520-0469(1986)043<0505:ASBFMU>2.0.CO;2.

Silva Dias PL. 2006. Background on other regional aspects: Land use change, aerosols and trace gases. In *Climate change in the La Plata basin*, Barros V, Clarke R, Silva Dias P (eds), Inter American Institute on Global Change (IAI); 127–139. http://www.atmos.umd.edu/~berbery/lpb/climate_change_lpb.pdf. Last access January 16, 2017.

Souma K, Sunada K, Suetsugi T, Tanaka K. 2013a. Use of ensemble simulations to evaluate the urban effect on a localized heavy rainfall event in Tokyo, Japan. *Journal of Hydro-environment Research* **7**: 228–235. DOI: 10.1016/j.jher.2013.05.001.

Souma K, Tanaka K, Suetsugi T, Sunada K, Tsuboki K, Shinoda T, Wang Y, Sakakibara A, Hasegawa K, Moteki Q, Nakakita E. 2013b. A comparison between the effects of artificial land cover and anthropogenic heat on a localized heavy rain event in 2008 in Zoshigaya, Tokyo, Japan. *Journal of Geophysical Research: Atmospheres* **118**: 11,600–11,610. DOI: 10.1002/jgrd.50850.

Tanaka K. 2004. Development of the new land surface scheme SiBUC commonly applicable to basin water management and numerical weather prediction model. *Doctoral Dissertation, Graduate School of Engineering, Kyoto University*, Kyoto; 289.

The Global Land Cover Facility. 2006. Forest Cover Change in Paraguay. Version 1.0, University of Maryland Institute of Advanced Computer Studies, College Park, Maryland, 1990–2000. http://glcf.umd.edu/data/paraguay/. Last access February 13, 2017.

Tsuboki K, Sakakibara A. 2007. Numerical prediction of high-impact weather systems – The Seventeenth IHP training course. http://www.rain.hyarc.nagoya-u.ac.jp/~tsuboki/cress_html/src_cress/CReSS2223_users_guide_eng.pdf. Last access January 16, 2017.

Tucker CJ, Pinzon JE, Brown ME, Slayback DA, Pak EW, Mahoney R, Vermote EF, El Saleous N. 2005. An extended AVHRR 8-km NDVI dataset compatible with MODIS and SPOT vegetation NDVI data. *International Journal of Remote Sensing* **26**: 4485–4498. DOI: 10.1080/01431160500168686.

UK Met Office. 2005. GHRSSST Level 4 OSTIA Global Foundation Sea Surface Temperature Analysis. Ver. 1.0. http://dx.doi.org/10.5067/GHOST-4FK01. Last access August 25, 2016.

Werth D, Avissar R. 2002. The local and global effects of Amazon deforestation. *Journal of Geophysical Research* **107**: LBA 55–1–LBA 55–8. DOI: 10.1029/2001JD000717.