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Deforestation-induced reduction in rainfall

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Borneo is the third largest island in the world and famous for its majestic rainforests (Figure 1a). Southeast Asian tropical forests have the highest relative deforestation rate in the world (Canadell *et al*., 2007). More than 80% of the total land area of Borneo was covered with pristine forest in the 1950s; however, the high deforestation rate (1.7% year^{-1}), which is almost double that of the already intense deforestation rate of the whole Southeast Asian region, has resulted in the current estimation of forest cover being ~50% (Langner *et al*., 2007) (Figure 1b). Since 1965, production of tropical hardwood timber in Borneo sharply increased and reached a plateau and maximum in the early 1980s (Brookfield and Byron, 1990). Although the recent and rapid decline in timber production has been evident throughout Borneo owing to over-logging, over the past decades, more timber was exported from Borneo than from tropical Africa and Latin America combined (Curran *et al*., 2004). The land cover area categorized as 'degraded forest and regrowth', 'cultivation forest mosaic' and 'dry/wet bare soil; grasslands; agriculture' reached up to 33 million ha, ~45% of the total area of Borneo (Langner *et al*., 2007).

Tropical forests are a major source of global hydrologic fluxes, and thus, this forest cover change has potential to significantly alter the global and regional climate and hydrologic cycling (Nobre *et al*., 1991; Kanae *et al*., 2001; Avissar and Werth, 2005). Because tropical rainforests exist where ecosystem water resources are greatest, the hydrologic changes could significantly alter ecological patterns and processes (Malhi *et al*., 2009; Phillips *et al*., 2009; Kumagai and Porporato, 2012), in turn affecting feedback to the atmosphere (Meir *et al*., 2006; Bonan, 2008). It is a matter of course that the drastic deforestation and forest degradation in Borneo should be anticipated to impact the regional hydro-climate; in fact, the long-term daily grid precipitation datasets (APHRODITE's Water Resources, available via http://www.chikyu.ac.jp/precip/, Yatagai *et al*., 2012) over Borneo showed a significant decline in precipitation over the period 1951–2007 (Figure 1c). An abrupt decline in precipitation in the late 1980s can be seen (Figure 1c), which was consistent with a time when deforestation, i.e. logging for timber production, might have become intensive (Brookfield and Byron, 1990; Curran *et al*., 2004). Furthermore, it should be noted that such a decreasing trend in precipitation might cause frequent extreme droughts and subsequent fires, resulting in more severe deforestation and forest degradation (van Nieuwstadt and Sheil, 2005; Wooster *et al*., 2012).

A spatial distribution of atmospheric moisture convergence averaged over 1998–2010 in the eastern Pacific Ocean (built using a reanalyzed and gridded four-dimensional meteorology dataset, Japanese 25-year ReAnalysis and the Japan Meteorological Agency Climate Data Assimilation System available via http://jra.kishou.go.jp/JRA-25/index_en.html) suggests less moisture convergence and divergence over Borneo compared with other regions (Figure 2a). On the other hand, the Tropical Rainfall Measuring Mission satellite measurements from 1998 to 2010 (NASA Goddard Earth Sciences Data and Information Services Center, available via http://disc.sci.gsfc.nasa.gov/about-us) showed a larger amount of precipitation above islands of the maritime continent in the western Pacific Ocean compared with sea areas,

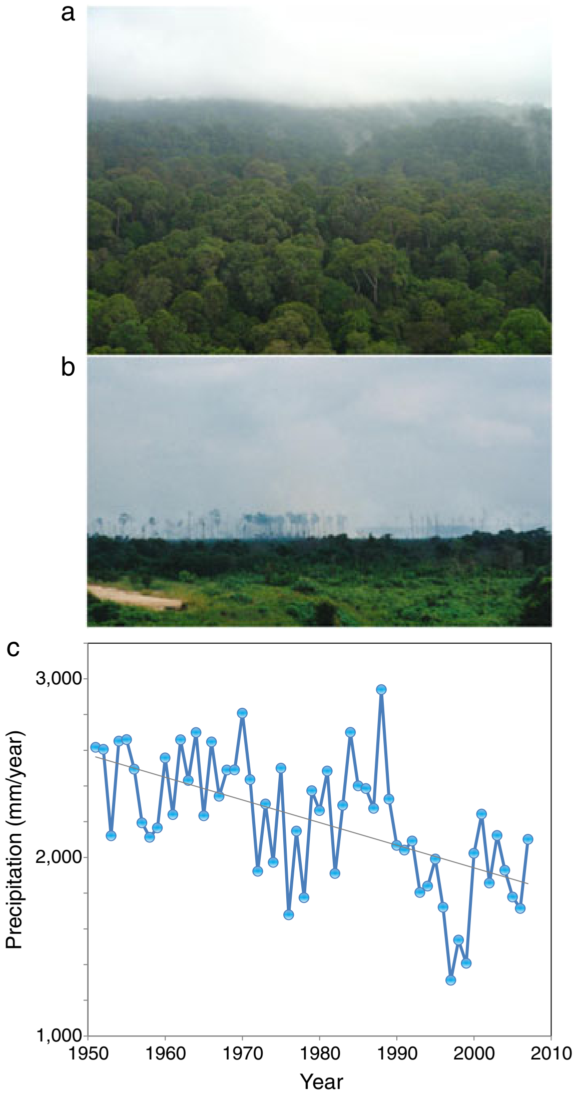

Figure 1. (a) A pristine Bornean rainforest with morning fog. (b) A rainforest being cleared and burned for conversion to an oil palm plantation. (c) The decreasing trend ($-12.7\,\text{mm year}^{-1}$) in annual precipitation integrated over Borneo, in the period 1951–2007. A significant regression line is also shown ($p < 0.0001$). Note that even though precipitation data in 1997 and 1998, when a strong El Niño event occurred and caused an extreme drought, were excluded, this decreasing trend was unchanged

suggesting a notably large amount of precipitation over Borneo (Figure 2b). In short, although little atmospheric moisture horizontally moves into and out of the atmospheric space over Borneo, this area has plenty of precipitation (Figure 2c).

Therefore, a question arises: where does water for precipitation come from? According to the atmospheric water budget equation, assuming that the time change of local available precipitable water content is negligible (Oki *et al.*, 1995), annual evapotranspiration over Borneo was roughly estimated to be ~7 mm day^{-1} and balanced with the annual precipitation, implying that most of the precipitation was recycled from terrestrial evapotranspiration over Borneo (Figure 2c). However, this evapotranspiration value surpassed the upper limit of the potential evaporation when taking into consideration basic meteorological variables in this region (Kumagai *et al.*, 2005). The computation of the budget equation using the combination of the reanalysis and the satellite measurement data, which are different in their derivations, might cause such a discrepancy. Nevertheless, in light of comparisons with the other areas, it is certain that there are large amounts of precipitation in, and little moisture advection into or out of, the Bornean region (Figure 2a, b). Also, a yearly eddy covariance observation conducted at a Bornean tropical rainforest site indicated the high rate of pristine rainforest evapotranspiration, which can be approximated using the same mechanism as the evaporation from an extensive water surface, to be ~4 mm day^{-1} as an annual mean (Kumagai *et al.*, 2005). Thus, we concluded that there is a higher ratio of recycling from terrestrial evapotranspiration into the precipitation over Borneo (Figure 2c) and that deforestation and forest degradation could alter this eco-hydro-climatological cycling.

Therefore, it is plausible that the deforestation and forest degradation has led to a long-term decline in precipitation in Borneo (Figure 1c). In addition, it was pointed out that a slowdown of the Walker circulation over the last 60 years suppressed moisture convergence over the maritime continent including Borneo, resulting in the historical decline in land precipitation (Tokinaga *et al.*, 2012). We argue that deforestation and forest degradation can be still a major factor inducing the decline in precipitation because such a weakening of moisture convergence would promote recycling of the terrestrial evapotranspiration into the precipitation.

Certainly, fire is the major driver for the deforestation and forest degradation in Borneo (Langner *et al.*, 2007), and evapotranspiration from lands where fires occur decreases appreciably. The land cover of deforested areas does not always end up as bare land; they are usually converted to other vegetation types like oil palm plantations (Carlson *et al.*, 2012) (Figure 1b). This suggests that the land cover change and deforestation does not necessarily decrease land evapotranspiration. Thus, a reliable assessment of the deforestation-induced impacts on the regional hydro-climate firstly requires new data on characteristics of energy and mass exchange between the atmosphere and the land surfaces resulting from the land conversion. For example, the flux data on oil palm plantations, a major resultant land cover (Carlson *et al.*, 2012), are seriously lacking for describing changes in the land surface process. Numerical experiments with cloud resolving models (e.g. The Weather Research & Forecasting Model available at http://www.wrf-model.org/index.php) using the land surface-atmosphere exchange data as well as satellite monitoring of land cover classification can help elaborate the reduction in precipitation from the deforestation and forest degradation over Borneo.

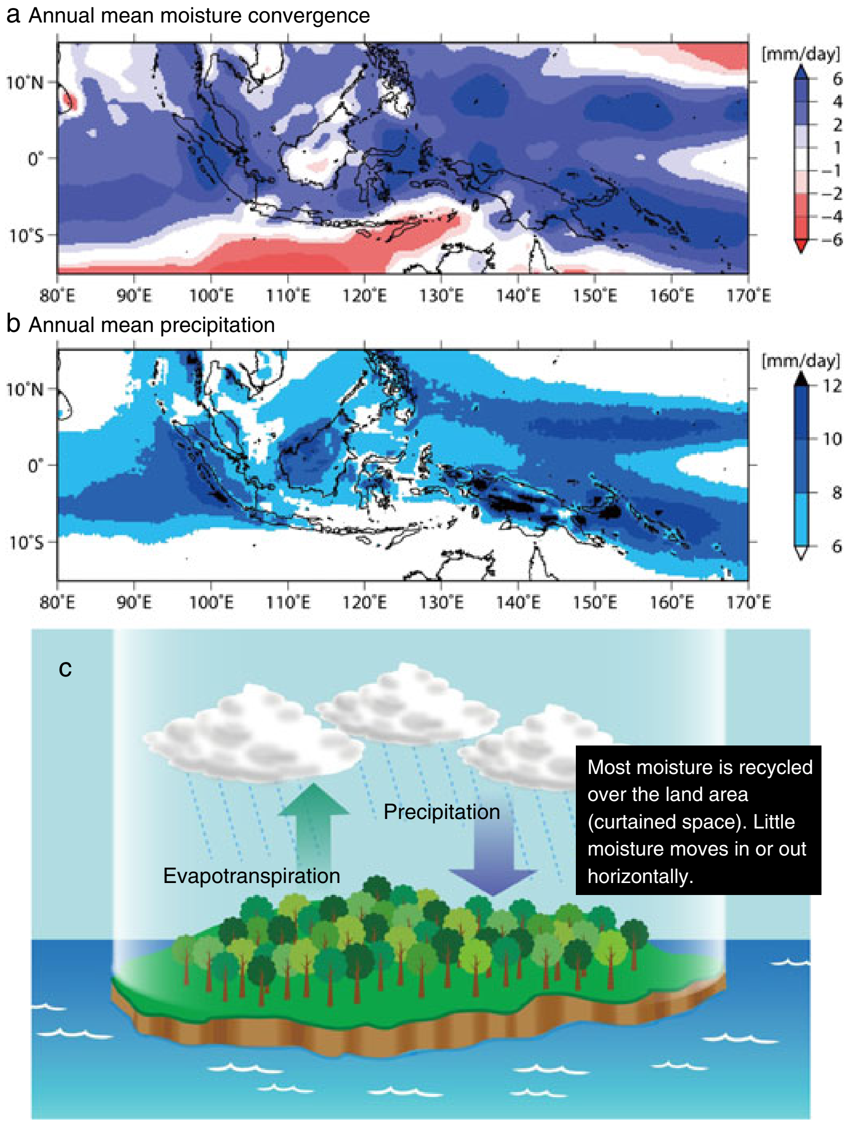

Figure 2. Maps of (a) annual mean moisture convergence and (b) annual mean precipitation in the western Pacific Ocean (constructed using Japanese 25-year ReAnalysis and Tropical Rainfall Measuring Mission satellite measurements 3B42 Ver.7 datasets, respectively, with values averaged over the period 1998–2010). (c) Schematic representation of hydrologic fluxes over Borneo

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