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Simulated response of the atmosphere-ocean system to deforestation in the Indonesian Archipelago

Christine Delire[1], Pat Behling[2], Michael T. Coe[1], Jonathan A. Foley[1], Robert Jacob[2,3],
John Kutzbach[2], Zhengyu Liu[2], and Steve Vavrus[2]

Abstract. The climatic effects of large-scale deforestation in the Indonesian Archipelago are investigated using a fully coupled atmosphere-ocean model -- the Fast Ocean Atmosphere Model (FOAM). Extremely rapid rates of deforestation across the Archipelago motivate this study. We compare two simulations (one with fixed ocean temperatures, another where the ocean responds to changing atmospheric conditions), to investigate the potential for oceanic feedbacks on deforestation-induced climate change. With fixed sea surface temperatures, evaporation decreases over land but increases over the surrounding oceans where the wind speeds increase. Regional deep convection is enhanced and precipitation increases over the islands. With an interactive ocean the initial decrease in evaporation over the deforested land reduces convergence and increases the easterlies in the Bay of Bengal. More intense equatorial upwelling cools the surface temperatures over that region and reduces ocean evaporation. Regional convection is less intense and precipitation drops by 9% over deforested land.

Introduction

The influence of deforestation on regional and global climates has been extensively studied with atmospheric models [e.g., *Dickinson and Henderson-Sellers*, 1988; *Nobre et al.*, 1991; *Lean and Rowntree*, 1993; *Sud et al.*, 1996; *Zhang et al.*, 1996 a,b, *Costa and Foley*, 2000]. However, to date, no study has examined how the fully coupled atmosphere-ocean system might respond to large-scale deforestation, and whether oceanic feedbacks may modulate the response of the climate system to deforestation.

Tropical forests, are associated with the major convective heating centers in Amazonia, Africa, and the Indonesian Archipelago. Deep moist convection transfers energy from the surface to the upper atmosphere (via evapotranspiration at the surface and condensation aloft) where it is redistributed to the whole tropical belt and to higher latitudes. Altering or removing tropical forests modifies the local energy balance, and therefore, affects regional convection. This change in magnitude and/or spatial distribution of convection alters the high-level outflow. Several studies have shown how changes in tropical land cover affect the climate of higher latitudes [*Sud et al.*, 1996; *Sellers et al.*, 1996; *Zhang et al.*, 1996].

We chose to study deforestation in the maritime continent of Malaysia, Indonesia, and New Guinea for several reasons. First, deforestation is occurring at a high rate in the region: 1 to 2 % per year from 1980-1990, compared to 0.3 % in Amazonia [*World Resource Institute*, 1999] due to economic and demographic pressure. Second, this region is a mix of islands and seas, making it more likely to exhibit interactions between land and ocean. Finally, the Indonesian Archipelago is located on the equator where the surface waters are very sensitive to surface winds and therefore deforestation might have an important impact on the local and regional climate.

Deforestation in the Indonesian Archipelago has not received the same attention from climate modelers as deforestation in Amazonia. It has only been studied as part of global tropical deforestation [*Mc Guffie et al.*, 1995; *Zhang et al.*, 1996; *Sud et al.*, 1996] or as part of historical land cover changes [*Chase et al.*, 2000]. In all cases, the studies were conducted with atmospheric global circulation models (AGCM) with fixed sea-surface temperatures [*Sud et al.*, 1996; *Zhang et al.*, 1996; *Chase et al.*, 2000] or with a mixed layer ocean [*Mc Guffie et al.*, 1995]. These studies showed a significant decrease in evapotranspiration over the region, but the decrease was smaller in magnitude than the changes obtained in the Amazon basin. Precipitation was reduced in most cases, although *Sud et al.* found increased precipitation rates over the islands. Possible explanations for the different response to Indonesian deforestation, compared to Amazonian deforestation, include smaller deforested areas, surrounding warm waters and the dominance of the large-scale Asian-Australian monsoon system. These studies clearly showed the need to include an interactive ocean to properly evaluate the effects of tropical land cover changes in the region.

Here we present a study of complete deforestation of Malaysia and the Indonesian Archipelago with a coupled atmosphere-ocean model. A complete deforestation of the region is unrealistic, but serves to illustrate the basic mechanisms and feedbacks involved.

Model Description

In this study, we use the Fast Ocean Atmosphere Model (FOAM) of *Jacob et al.* [1997]. FOAM was designed to achieve

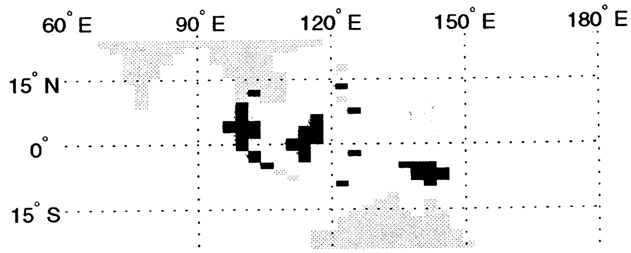

Figure 1. Location of tropical evergreen broadleafed forest in FOAM (darkshading) clear-cutted in our deforestation simulations.

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[1] Center for Sustainability and the Global Environment (SAGE), Institute for Environmental Studies, University of Wisconsin, Madison.

[2] Department of the Geophysical Sciences, The University of Chicago, IL.

[3] Now at Argonne National Laboratory, Mathematics and Computer Science Division

[4] Center for Climatic Research, Institute for Environmental Studies, University of Wisconsin, Madison.

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Table 1. Vegetation characteristics for the forested and deforested (grassland) cases.

Vegetation type	albedo	roughness length (m)
Tropical evergreen broadleaf forest	0.14	2.0
Tall/medium grassland	0.19	0.1

long climate simulations by combining medium resolution and massive parallelism. The atmosphere model, PCCM3-UW, uses the physics of the NCAR CCM3 and the parallel numerics of the NCAR/Argonne/Oak Ridge PCCM2 at a resolution of R15 (about 4.5^0 x 7.5^0). The ocean model, OM3, is similar in concept to the GFDL's MOM model but uses a 128x128 point grid (1.4^0 x 2.8^0) and numerical methods designed for massively parallel platforms. FOAM's low computational cost allows it to be run economically for several hundreds of years. The model has a mean tropical climate that compares well against observations and similar models with the same or higher resolution. FOAM also simulates decadal variability in the midlatitudes and tropics, ENSO variability and a 50 year thermohaline oscillation (*Jacob et al.*, 2000, "Simulated low frequency variability in a mixed resolution coupled GCM, in prep). The land-surface scheme is a 15 cm deep bucket hydrology model. This land-surface scheme uses the *Matthews* [1983] vegetation types merged into 10 classes including croplands. The vegetation types differ mainly in their albedo and roughness length. Associated soil types differ in their thermal characteristics. Although extremely simple, this scheme is able to simulate the major physical processes acting at the land surface and how they differ in forests and grasslands.

Numerical Simulations

We first ran the coupled ocean-atmosphere model for 450 years to reach equilibrium. We then performed a total of four simulations: two with the coupled ocean-atmosphere model (DYNO) and two with fixed SSTs (FSST), beginning with year 450 of the equilibrium run. In both cases we performed a forested (F) simulation and a deforested (G) simulation in which we replaced all the "Tropical evergreen broad-leafed" forest in Indonesia by "Tall/medium grassland" (Fig. 1, Table 1). Southeast Asia is left almost unchanged because the vegetation dataset used in the forested case [*Matthews*, 1984] has cropland and other forest types in the region.

The two dynamical ocean simulations (DYNO-F and DYNO-G) were run for 150 years. The fixed SST simulations (FSST-F and FSST-G) were run for 15 years using the monthly mean SSTs from the forested dynamical ocean run. We analyzed the last 120 years of the 150-year integration with the dynamic ocean and the last 10 years of the fixed SST runs.

Results With Fixed Sea-surface Temperatures

With fixed sea-surface temperatures, the model simulates an annual average decrease of nearly 10 W m^{-2} in net radiation and latent heat flux over the deforested land (Table 2). Those values compare well with previous simulations done with different atmospheric models and more detailed land-surface schemes [see e.g. *Zhang et al.*, 1996]. The physical processes explaining these changes in energy balance have been extensively discussed in the literature [e.g. *Zhang et al.*, 1996; *Sud et al.*, 1996]. The higher albedo of the grassland (Table 1) reduces the amount of solar energy absorbed by the surface. The reduced available energy and the smaller roughness length of the grass in this model, and in some other studies the shallower roots and the smaller leaf area index, reduce the latent heat flux. In the case of simulations of Amazon deforestation [e.g. *Zhang et al.* 1996; *Nobre et al.*, 1991], it has been shown that precipitation decreases because the reduced evaporation over land is not compensated by an influx of moisture from neighboring regions. In the Indonesian case, the neighboring regions are warm oceans with fixed SSTs that can provide a limitless supply of energy to the atmosphere above. Deforestation reduces roughness on the islands, increasing wind speed both over land and the surrounding oceans for most of the year. The increased wind speeds extract greater latent and sensible heat from the ocean. This unrealistic heating of the lower atmosphere produces dynamical responses altering the atmospheric circulation: vertical velocity is increased by up to 15 % in the mid troposphere and precipitation over land increase by 0.27 mm/day (4%).

Effects of Ocean Feedbacks.

When the ocean is allowed to respond to the change in wind speeds, the evaporation decreases over the neighboring oceans, mainly northwest of the Archipelago in the Bay of Bengal (not shown). The mechanism explaining this feature involves a change in the low level winds. During boreal winter, the mean flow travels from north to south from the Siberian high to the ITCZ (Fig 2a). Because of the Coriolis effect, the islands north (south) of the equator experience northeasterly (northwesterly) winds. During boreal summer the pattern is reversed: southeasterly flow south of the equator and southwesterly flow north of the equator. The intermediate months show a transition pattern from

Table 2. Area and annual averaged simulated energy and moisture fluxes over the deforested gridcells

Flux	FSST		DYNO	
	Forest	Grass	Forest	Grass
R_n (W m^{-2})	178.4	169.6	178.2	168.9
H (W m^{-2})	42.3	41.1	46.5	53.3
LE (W m^{-2})	136.1	128.5	131.7	115.6
Precip (mm day^{-1})	6.64	6.91	6.37	5.82
Evap (mm day^{-1})	4.68	4.42	4.53	3.98

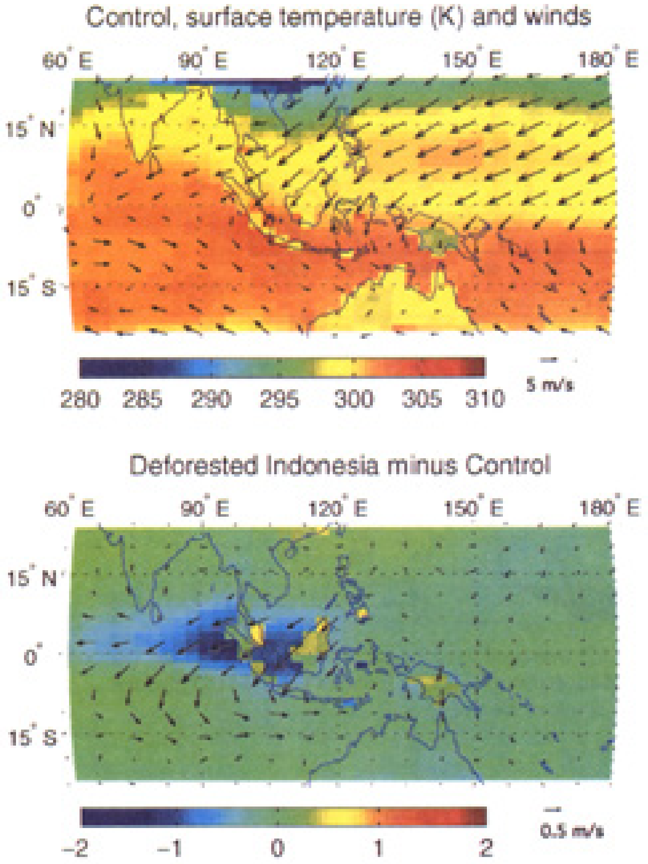

Figure 2. Mean surface winds and surface temperature (K) for December to May simulated by FOAM averaged over 120 years. (a) Forested run (DYNO-F) (b) Difference between forested and deforested runs (DYNO-F minus DYNO-G).

boreal summer to winter and vice-versa. The December to May average of the surface winds is dominated by the north-south winter pattern (Fig. 2a). Following deforestation, increased atmospheric pressure leads to strengthened easterlies north of the equator and weakened westerlies from 0 to 5 S (Fig. 2b). As a result, divergence of the surface waters on the equator west of the islands is enhanced and upwelling is favored. In the forested case, upwelling occurs to the west of the islands from December to February. In the deforested case, the equatorial upwelling persists until May and the upwelling is more intense from December to February. This upwelling brings deeper colder water to the surface for more than 6 months of the year and lowers the sea-surface temperatures West of the islands by up to 1.5 C (Fig. 2b). The cooler surface creates an anticyclonic anomaly in the atmosphere from the Bay of Bengal to Java and Borneo that reinforces the original wind changes and further enhances equatorial upwelling. The sea-surface cooling and wind changes are qualitatively similar to the observed anomalies in the eastern Indian Ocean in November and December 1997 [*Webster et al.*, 1999], when the Archipelago experienced severe drought. Deforestation in this model thus produces a response that is similar to the dipole mode in the Indian Ocean when the eastern part of the basin experiences anomalous cool sea-surface temperatures and drought conditions on land [*Saji et al.*, 1999].

During the other months of the year, when the wind flow is reversed, there is little change in the wind speeds after deforestation. For the annual mean, the Indian Ocean around the equator and the waters between the islands are cooler by about 0.5 degrees with deforestation. Averaged over 9N-9S and 90E to 150E, the latent heat flux is decreased by 2.5 W m^{-2}. The area where the latent heat flux decreases is more than 4 times larger than the deforested areas themselves (2.14 10^6 km^2) and twice as big as the area of the Amazonian rainforest. Convection is less active as shown by the general decrease (10 to 15 %) in upward vertical velocity averaged from 9N to 9S (Fig. 3) and the decrease in rainfall (Table 2). The decrease in deep convective activity over the region affects the entire tropics, as evidenced by a 10 m decrease in the geopotential height at 100 mb over the whole equatorial belt (not shown). In the fixed SST case, convection increased because the reduction in land evaporation was compensated by increased ocean evaporation.

The increased surface wind speeds to the west of the islands in the Indian Ocean are due to two processes. First, the reduced net radiation and latent heat flux over the land increases surface pressure and reduces convergence, causing increased easterlies west of the islands. Second, replacing tropical forest by grassland reduces the roughness of the surface (Table 1) and increases the surface winds. In order to test the relative importance of those two processes, we conducted a sensitivity study where we only changed the albedo as appropriate for a forest to grassland transition, while keeping roughness at the value for forest. The latter simulation is not unrealistic: because of the coarse spatial resolution of FOAM, the friction due to vegetation is probably overestimated in comparison to the friction due to the orography in those highly mountainous islands. We obtain a change in wind speed over the Indian ocean that is similar to the DYNO-G case: strengthened easterlies north of the equator and weaker westerlies from 0 to 5S (not shown). Consistent with no change in the roughness value, the change in wind speed is less important over the islands. The cooling of the surface waters is less intense (0.5 C from December to May) but the combination of wind and temperature change results in a more extensive region where the latent heat flux is reduced (6 times larger than the deforested area). The precipitation over the islands drops by 3 %. Reduced convergence due to the decreased net radiation and latent heat flux over land is thus the main driver of the wind, temperature and evaporation changes we obtain over the Indian Ocean.

Conclusions

In this study, we used a coupled atmosphere-ocean model to investigate the effects of a complete deforestation of the Indonesian Archipelago on local energy balance, climate of the neighboring Indian Ocean and moist convection over the region. We found that the initial decrease in latent heat flux over land reduces convergence and modifies the wind patterns over the oceans, increasing equatorial upwelling in the Indian Ocean and cooling the sea-surface temperatures. Evaporation over the ocean decreases, further reducing convergence over the region. These initial atmosphere-ocean model simulations show that the ocean can amplify a relatively small signal on land. Thus, the importance of deforestation on the climate of this region has been probably underestimated in previous studies that did not use a dynamic ocean model. There are several caveats associated with these results: (1) the land-surface scheme in FOAM is particularly crude and should be replaced by a model of the vegetation based on physiological and biophysical processes, (2) the horizontal resolution of the atmosphere in FOAM is low. However, the results of the sensitivity study to the roughness length increase our confidence in the robustness of the mechanism. Overall, because of the geographical uniqueness of the region, it is likely that a change in the land surface will have

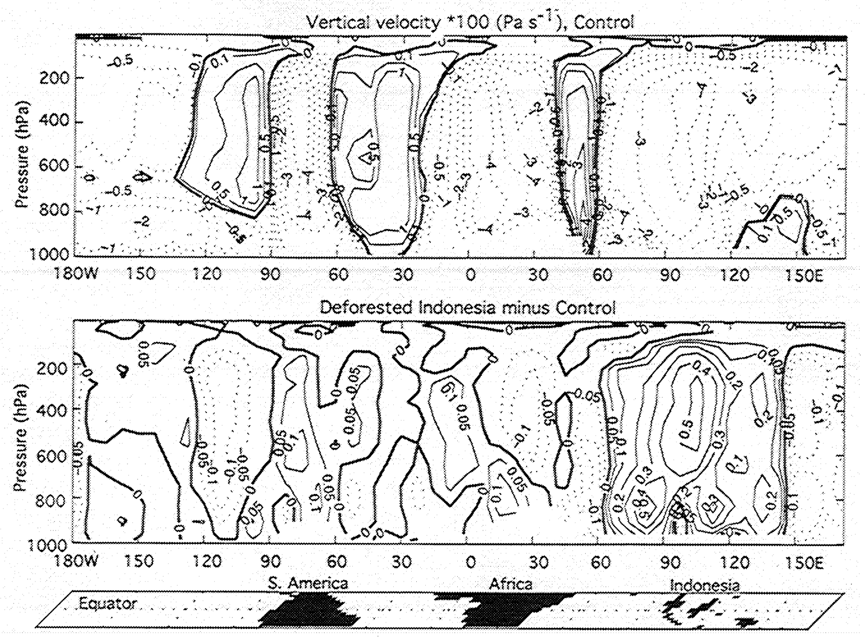

Figure 3. Profile of the annual mean vertical velocity (10^{-2} Pa s^{-1}) averaged over 9N to 9S and over 120 years. (a) Forested run (DYNO-F) (b) Difference between forested and deforested runs (DYNO-F minus DYNO-G). Negative values indicate upward motion. (c) Map of the equatorial regions between 9N and 9S.

an important impact on the surrounding oceanic climate, with potential feedback on the climate at higher latitudes.

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C. Delire, M. T. Coe and J. A. Foley. P. Behling, Center for Sustainability and the Global Environment (SAGE), Institute for Environmental Studies, University of Wisconsin, 1225 W Dayton St., Madison, WI, 53706-1695, USA. (email: cldelire@facstaff.wisc.edu)

R. Jacob, Argonne National Laboratory, Mathematics and Computer Science Division, 9700 S. Cass Avenue, Building 203, C240 Argonne, IL 60439-4843, USA.

J. Kutzbach, P. Behling, Z. Liu, and S. Vavrus, Center for Sustainability and the Global Environment (SAGE), Institute for Environmental Studies, University of Wisconsin, 1225 W Dayton St., Madison, WI, 53706-1695, USA.

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