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On the non-linear response of the ocean thermohaline circulation to global deforestation

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[1] An experiment of 1750-yr duration has been performed with a three-dimensional coupled atmosphere-sea-ice-ocean-vegetation model to study the transient effect of global deforestation on climate. The response consists of two phases. First, the initial global cooling due to increased surface albedo (forest replaced by grassland) is enhanced by a significant expansion of the sea-ice cover in both hemispheres, which increases the surface albedo further. Second, a non-linear response of the ocean thermohaline circulation results in a southward shift of the main deep-convection site and reduced northward heat transport in the Atlantic Ocean, leading to enhanced global cooling due to a further expansion of Arctic sea ice. Ultimately, surface temperatures over northwestern North America become sufficiently low to prevent the snow pack to melt in summer. Our results thus suggest that large-scale changes in forest cover may lead to non-linear changes in the climate system. *INDEX TERMS:* 1620 Global Change: Climate dynamics (3309); 4255 Oceanography: General: Numerical modeling; 0315 Atmospheric Composition and Structure: Biosphere/atmosphere interactions; 1635 Global Change: Oceans (4203). **Citation:** Renssen, H., H. Goosse, and T. Fichefet, On the non-linear response of the ocean thermohaline circulation to global deforestation, *Geophys. Res. Lett.*, *30*(2), 1061, doi:10.1029/2002GL016155, 2003.

1. Introduction

[2] It has been widely recognized that large-scale changes in vegetation can lead to significant climate changes [*Stocker et al.*, 2001]. For instance, anthropogenic deforestation in the tropics during the last few decades is known to have resulted in reduced evaporation and increased surface temperatures [*Gash et al.*, 1996]. Many studies have shown that climate models are able to qualitatively reproduce these effects [e.g., *Lean and Rowntree*, 1997; *Hahmann and Dickinson*, 1997].

[3] Less consideration, however, has been given to the sensitivity of climate to large-scale land-surface changes on longer time-scales (centuries to millennia). Ideally, this should be studied in transient experiments with coupled atmosphere-ocean-biosphere models. This issue is relevant for the future climate, as it is expected that the increase in global population will alter the surface of the Earth significantly in the next centuries (e.g., further deforestation [*Pahari and Murai*, 1999]). It is also important for our understanding of past climate changes, as the characteristics of land surfaces were very different during some periods in the past. For instance, during the last glacial maximum (21 thousand years ago), the land area covered by forests was greatly reduced [e.g., *Crowley and Baum*, 1997], and further back in time, at the Cretaceous-Tertiary boundary (65 million years ago), a giant bolide impact probably caused global deforestation [*Vajda et al.*, 2001].

[4] To our knowledge, the only coupled model study in which the long-term climatic effect of large-scale deforestation has been assessed is that of *Claussen et al.* [2001]. These authors have investigated the impact of boreal and tropical deforestation in a coupled atmosphere-ocean-biosphere model of intermediate complexity. Two effects of deforestation were discovered. First, a biogeophysical effect, in which changes in land-atmosphere interactions are caused by altered physical properties of the land surface, of which the surface albedo is the most important. Second, a biogeochemical effect, in which deforestation leads to climate change through an increase in atmospheric CO_2 concentration. *Claussen et al.* [2001] found that in their model boreal deforestation induces a cooling, especially at high latitudes, mainly due to the positive snow-vegetation-albedo feedback (a biogeophysical effect). Tundra has a higher albedo than forests, especially when snow-covered, and thus causes cooling, yielding an expansion of sea ice, which further reduces surface temperatures. Deforestation in the model tropics, however, led to global warming due to a combination of biogeophysical and biogeochemical feedbacks. According to *Claussen et al.* [2001], the most important biogeophysical effect at low latitudes is the reduction of evaporation over the deforested areas, causing an increase in the sensible heat flux, which produces regional warming.

[5] The aim of the present study is to further study the transient response of the climate system to a large-scale land-surface change at the centennial-to-millennial time-scale. To do so, we perturbed a pre-industrial simulation performed with a coupled atmosphere-sea-ice-ocean-vegetation model by removing abruptly all trees on Earth. As our model does not include a carbon-cycle model, we only consider the biogeophysical effect in our analysis. It is important to note that the 3-dimensional formulation of the coupled atmosphere-sea-ice-ocean-vegetation system in our model is much more comprehensive than the 2.5-dimensional representation in the model used by *Claussen et al.* [2001]. In addition, our model has an atmospheric component that simulates synoptic variability associated with weather patterns. As we will show in this paper, in our model, global deforestation results in a non-linear response of the ocean thermohaline circulation that has not been reported before. Our results thus add to our

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understanding of the sensitivity of the climate system to large-scale land-surface changes.

2. Model and Experimental Design

[6] We performed our experiment with the 3-dimensional, global ECBilt-CLIO-VECODE climate model. This model consists of three components representing dynamics of the atmosphere, ocean-sea ice and vegetation. The atmospheric component is ECBilt2, a spectral quasi-geostrophic model with three vertical levels and a T21 horizontal resolution [*Opsteegh et al.*, 1998]. It includes simple parameterizations for the diabatic heating due to radiative fluxes, the release of latent heat and the exchange of sensible heat with the surface. A full hydrological cycle is included, that is closed over land by a bucket model for soil moisture and runoff. Cloud cover is prescribed according to present-day climatology [*Rossow et al.*, 1996]. The ocean-sea-ice component, CLIO, consists of a free-surface, primitive-equation oceanic general circulation model with 20 vertical levels and 3° × 3° latitude-longitude resolution, coupled to a comprehensive dynamic-thermodynamic sea-ice model [*Goosse and Fichefet*, 1999]. The ECBilt-CLIO model reproduces reasonably well the modern climate [*Goosse et al.*, 2001]. It has been used to study meltwater-induced abrupt climate events during the early Holocene [*Renssen et al.*, 2001, 2002], natural variability of the modern climate [*Goosse et al.*, 2002a] and future climate evolution [*Goosse and Renssen*, 2001; *Schaeffer et al.*, 2002]. The model's response to a doubling in atmospheric CO_2 concentration is 1.8°C, which is on the low end of the estimated range. ECBilt-CLIO has been recently coupled to VECODE, a model that simulates the dynamics of three main terrestrial vegetation types: forest, grassland and desert [*Brovkin et al.*, 2002]. It should be noted that the computed vegetation changes only affect the land-surface albedo in ECBilt-CLIO, and have no influence on other processes, e.g., soil hydrology. The only flux correction required in ECBilt-CLIO-VECODE is an artificial reduction of precipitation over the North Atlantic and Arctic Oceans, and a homogeneous distribution of this removed amount of freshwater over the North Pacific Ocean [*Goosse et al.*, 2001].

[7] As a first experimental step, the model was run with forcings kept constant at pre-industrial values (AD 1750) until a quasi-equilibrium state was reached after 1600 years. The global fractions of forest, grassland and desert in this state amount to 42%, 40% and 18%, respectively. Subsequently, to introduce the effect of a sudden global deforestation, the forest fraction in all grid cells was fixed at zero (i.e., forest was replaced by grassland). After this perturbation, a new equilibrium vegetation was established within 100 years, with global fractions of grassland and desert of 80% and 20%, respectively. The model was run for 1750 years after the perturbation to study the long-term response of the atmosphere-sea-ice-ocean system to global deforestation. During these 1750 years, the forest fraction was kept equal to zero.

3. Results

[8] The instantaneous deforestation abruptly increases the global surface albedo by 2.6%. As expected, this abrupt albedo change is accompanied by a sudden reduction in global mean surface temperature, with a drop from 15.2°C in the pre-industrial equilibrium to 14.1°C after the perturbation (Figure 1a). Subsequently, the temperature gradually decreases further to 12.8°C around year 600. This gradual cooling phase is associated with the ice-albedo feedback, as can be seen from the build-up of sea ice in both the Northern and Southern Hemispheres in Figures 1b and 1c, respectively, increasing the global surface albedo further (by 1.6%). The annual mean sea-ice area in the Arctic increases from 11.7 to 14.7×10^6 km^2 and in the Southern Ocean from 7.9 to 13.0×10^6 km^2.

[9] Around year 660, a second, more gradual decline in temperature occurs from 12.8°C to values around 12.3°C. This second decline is caused by a change in oceanic circulation. Actually, the thermohaline circulation (THC) in the Atlantic Ocean responds to the deforestation in two phases (Figure 1d). First, a strengthening of the THC is observed, with the export of North Atlantic Deep Water at 20°S increasing from 15 Sv (1 Sv = 10^6 m^3 s^{-1}) in the pre-industrial equilibrium to an average of 21 Sv around year 600. This THC strengthening is the expected response to surface cooling, as it increases the density of the surface waters in the North Atlantic, thus promoting deep mixing. The resulting increase in northward heat transport by the Atlantic Ocean (from 0.28×10^{15} to 0.38×10^{15} W at 30°S) is however not sufficient to fully compensate for the cooling in the Northern Hemisphere due to the increase in surface albedo. At the start of the second phase, the THC weakens abruptly around year 660, i.e., simultaneously with the start of the second temperature decline.

[10] Analysis of the simulated overturning circulation reveals that the abrupt weakening of the THC is associated with a shift of the deep-convection area in the Nordic Seas. Until year 660, the main site of deep convection is located just south of Svalbard (75°N). The expansion of the sea-ice cover in this region stabilizes the upper ocean and reduces deep mixing, leading to a relocation of the deep convection between Iceland and Norway (66°N). After year 660, the THC is still stronger than before the deforestation (16.5 Sv exported at 20°S, Figure 1d) due to the relatively cool surface waters. The shift in deep-convection area is accompanied by a further expansion of sea-ice cover in the Northern Hemisphere (from 14.7 to 16.3×10^6 km^2), mainly because the Nordic Seas become ice-covered. The latter sea-ice expansion leads to an increase in global surface albedo by 0.6%. After year 750, a new state is established that remains stable for at least 1000 years.

[11] To test the robustness of the non-linear THC response to global deforestation, we have restarted the model three times before the THC weakening, i.e. at year 500, 550 and 600, with exactly the same set-up except for very small initial perturbations in the fluxes at the atmosphere-ocean interface. In all three cases, the overall response of the THC was similar to the standard experiment, although the timing of the THC weakening was somewhat different (at t = 730, 655 and 915). This suggests that the THC response to deforestation is a robust feature in our model, but that the exact timing of the weakening is unpredictable.

[12] A similar non-linear response of the THC to global cooling was found by *Wang et al.* [2002], who have run their intermediate-complexity coupled model with a gradual

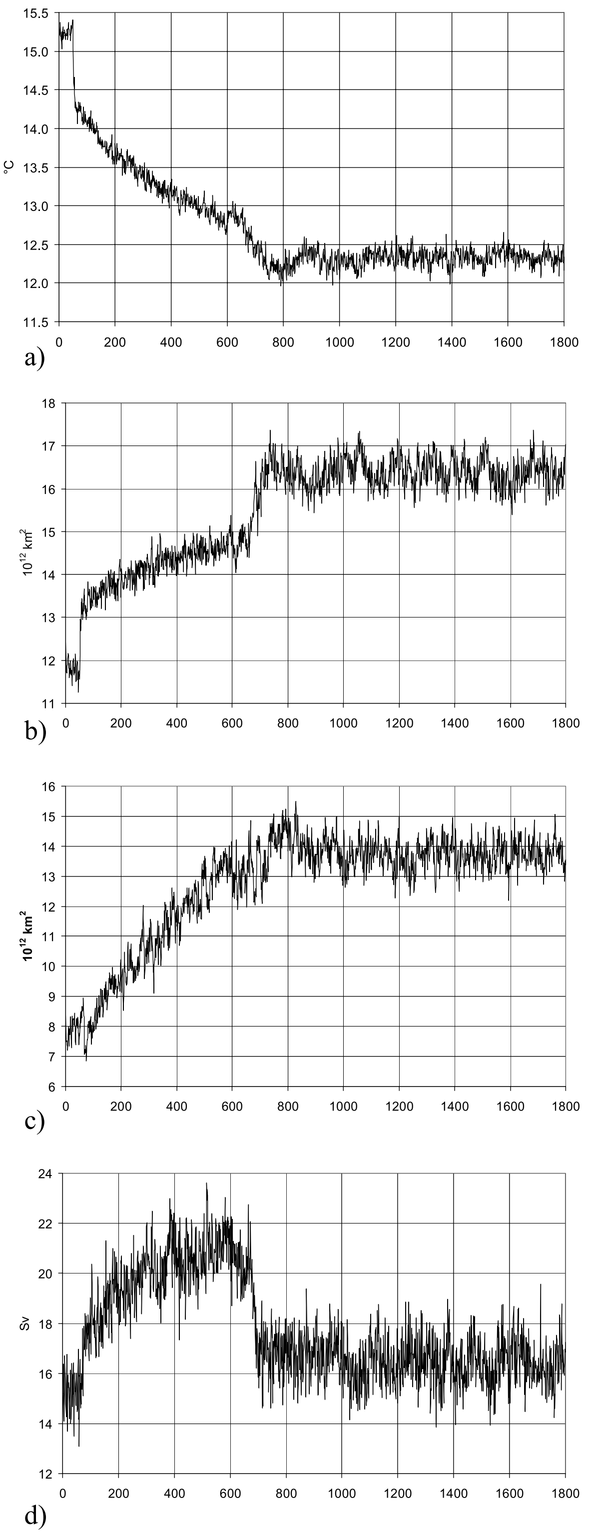

Figure 1. 1800-year time-series of annual mean values of several model variables, with the first 50 years representing the pre-industrial equilibrium: (a) global mean surface temperature (°C), (b) Northern Hemisphere sea-ice area (10^{12} km^2), (c) Southern Hemisphere sea-ice area (10^{12} km^2) and (d) southward export of North Atlantic Deep Water at 20°S (Sv).

increase in planetary emissivity. Interestingly, in the latter study, the global temperature at which the THC starts to weaken is 12.6°C, which is close to the value of 12.8°C reported here. A comparable change in deep-convection pattern has also been found in previous simulations with ECBilt-CLIO. In very rare occasions, such a change can occur spontaneously (i.e., twice in a 13,000-yr control simulation with forcings corresponding to pre-industrial conditions, [*Goosse et al.*, 2002b]). In addition, a reorganization of deep convection can be triggered by adding realistic freshwater pulses to the North Atlantic [*Renssen et al.*, 2001, 2002] or by reducing the solar constant by 5 Wm^{-2} [*Goosse et al.*, 2002b]. In the latter case, the cause of the shift is the radiative cooling of the atmosphere, just as in our case of global deforestation. However, the transitions in convection sites described in *Goosse et al.*, [2002b] are transient features that last for a few hundred years at most. In the deforestation experiment presented here, the decrease of temperature is larger. As a result, sea ice is able to survive during a long time in the region close to Svalbard and the cooling induces a permanent shift in convection site (i.e., at least 1000 years). It appears thus that the state of the THC with convection only in the southern part of the Nordic Seas was meta-stable for pre-industrial conditions [*Goosse et al.*, 2002b], while it is probably the only stable one in the state with global deforestation.

[13] The global distribution of the temperature response to deforestation exhibits after the second temperature decline a maximum cooling (−20°C) over the initial deep-convection area in the Nordic Seas, which has become ice-covered (Figure 2a). The expansion and thickening of sea ice also

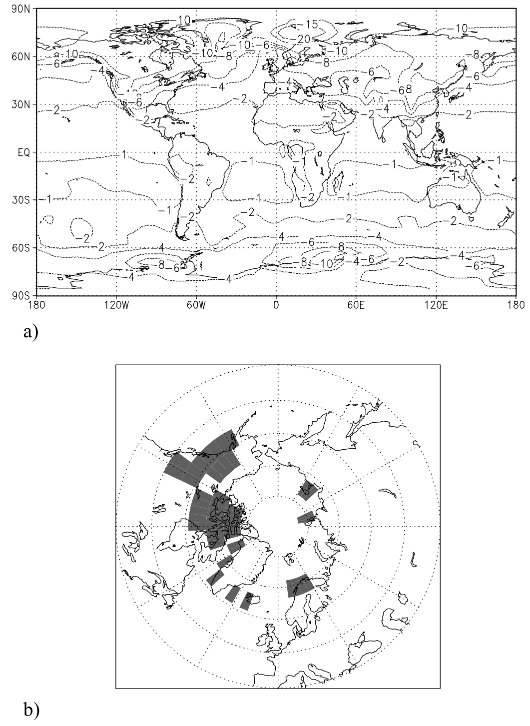

Figure 2. (a) Deforested state (year 750–800) minus pre-industrial (year 1–50) annual mean surface temperature (°C) anomalies. (b) Grid cells with an increase in August mean snow depth of more than 9 m (shaded, year 750–800 relative to year 1–50).

resulted in substantial cooling (−6 to −10°C) over the Arctic and Southern Oceans. In addition, over North America, the low surface temperature (more than 10°C cooling) is associated with the survival of snow during summer, i.e., amplification of cooling by the snow-albedo feedback. Especially over northwestern North America, a snowpack of more than 9 m thick has accumulated after the second temperature decline (Figure 2b). In the applied climate model, 10 m is the maximum snowpack thickness allowed to avoid excessive snow accumulation on ice sheets (Greenland and Antarctica) and thus a strong salinity drift in the ocean. As a result of the preset limit in maximum snowpack thickness, we are unable to simulate the initiation of ice-sheet growth in North America. Nevertheless, our results suggest that potentially global deforestation (due to, e.g., a meteorite impact) is able to cause glacial inception.

4. Conclusions

[14] We have performed a sensitivity experiment of 1750-yr duration with a three-dimensional coupled atmosphere-sea-ice-ocean-vegetation model to study the long-term, transient impact of complete deforestation on climate, thereby only considering biogeophysical processes. In our experiment, the system responds in two distinct phases.

[15] In the first phase, the initial global cooling of 1.1°C due to the change from forest to grassland is amplified during 600 years (additional 1.3°C global cooling) by the expansion of sea ice in both the Northern and Southern Hemispheres, which increases the surface albedo. At the same time, the oceanic overturning circulation strengthens due to cooling of the ocean surface waters that enhances the surface density and deep mixing.

[16] In the second phase, because of the large cooling in polar regions, the THC weakens abruptly and the main site for deep convection shifts southwards by 9 degrees of latitude, from south of Svalbard to east of Iceland. This modification yields further expansion of sea ice in the Northern Hemisphere and enhancement of the global cooling by 0.5°C. This in turn leads to survival of the summer snow pack in northwestern North America and northern Eurasia.

[17] These results may help to better understand the biogeophysical effects of deforestation on climate, such as due to the meteorite impact at the Cretaceous-Tertiary boundary or to global population growth in the next centuries.

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