CHAPTER 3

Interactions between climate characteristics and forests

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1. Introduction

A large knowledge about climate and vegetation interactions is indispensable for estimating human implications in climate and land cover changes.

Highlighting the forest system's contribution to the regional climate leads naturally to a concern about the possible impacts of the forest cover loss which is the current trend, along with the increased density of agricultural production and the acceleration of land clearing activities etc. Nevertheless, the impact of such actions is extremely difficult to evaluate because the cause and effect links between the forest and climate are not yet clearly understood (Brou Yao, 1997).

Indeed, numerous uncertainties still remain about the knowledge of vegetation-climate relationships under tropical latitudes and about the part of the anthropogenic forcing on the current climatic evolution at the global scale. Nevertheless, the human impact on local surface conditions is obvious at least at the regional scale of forest conversion, where hydrological changes are clearly connected to an increase of agricultural activities. Also, the biophysical relationship between land cover types and the local atmospheric environment is relatively well understood in principle, but the quantification of the processes still remains uncertain.

Knowledge on the current and future impact of human driven land change on climate in the Congo Basin, perhaps the most understudied tropical forest region of the world, can be improved using models, given the cost and difficulty of collecting ground-based information in the region. But we have to accept large uncertainties, especially when working at various scales.

Photo 3.1 : Tali (Erythrophleum ivorense) is a species that has a large distribution area in Central Africa and elsewhere

2. Vegetation – climate relationship

2.1 Biophysical interaction between forest and climate

The forest system, because of its great propensity for solar energy absorption and its capacity for evaporation, plays the role of an enormous energy converter. For example, forests convert water to water vapor (much like sweating) and provide shade more than other vegetation cover, which can lead to cooler surface temperatures (decreased upward longwave radiation). Indeed, the forest system absorbs the solar energy to limit heating and to vaporize water that its root system extracts from the soil (Monteny, 1987; cited by Mahé *et al.*, 2004). In the Tropical regions where horizontal temperature gradients are weak, the atmosphere is very sensitive to land and ocean surface conditions (relief, albedo, temperature, humidity, vegetation), which influence the distribution and the intensity of heat sources and heat sinks (Fontaine *et al.*, 1998a, 1998b).

The resulting exchanges of energy that forests maintain with the atmosphere influence the physical air mass parameters of the atmospheric layer closest to the earth (Monteny *et al.*, 1996).

Polcher (1994) catalogues three characteristics that determine the sensitivity of the climate to surface processes:

(i) the density of the forest system is such that the albedo (the amount of incoming solar energy reflected by a surface back to the atmosphere) is very weak compared to that of bare ground;

(ii) the high rate of evaporation, comparable to that of oceans, is one of the main characteristics of forests whose leaf density allows them to intercept and re-evaporate a large part of rainfall. The root systems of trees allow them to extract water from a greater portion of the soil than could be done in any other surface system;

(iii) the surface variation caused by the different heights of trees that make up the forest generates turbulence, which is favorable to triggering precipitation.

For Fontaine and Janicot, (1993), the two key parameters that forests influence are albedo and moisture. These parameters are closely linked, since wet ground, whether covered with vegetation or not, has a weaker albedo and greater evaporation capacity than the same ground, bare and dry.

Photo 3.2: The forest and water vapor are closely linked in ecophysiological functioning

Box 3.1: *Albedo*

The albedo (α) of a surface is the ratio between reflected and incoming solar radiation. It varies between 0 for a perfect black body that absorbs all the incoming radiation to 1 for a surface that reflects it all. It depends on the wavelength, but the general term usually refers to some appropriate average across the spectrum of visible light, or across the whole spectrum of solar radiation.

Source: http://www.elic.ucl.ac.be/textbook/glossary_a.html#albedo

In tropical regions the dense forest is closely integrated in the water cycle.

The quantity of water precipitated on the continent comes primarily from the condensation of water vapor accumulated in the air masses as they pass over the ocean and secondly via evapotranspiration, which is the water that is transpired by vegetation as they assimilate carbon or evaporated from the surface. Whereas moisture from the ocean has a clear connection to regional and global climatic processes, evidence shows that vegetation recycles moisture primarily locally, with more recent evidence showing potential regional influences as well (Bigot, 1997; Bonell, 1998). Indeed, recent studies have shown that the Congo Basin land cover influences the rainfall in Sahara, Ethiopia, and other parts of the continent.

The concentration of water vapor in the air mass coming from the ocean and which then crosses the continent depends also on the evaporation process of the vegetation-atmosphere interface. It has been shown in central Africa (Figure 3.1) that a large part of moisture transfer into the atmosphere (evapotranspiration), contributes to the formation of cloud systems (Bigot,

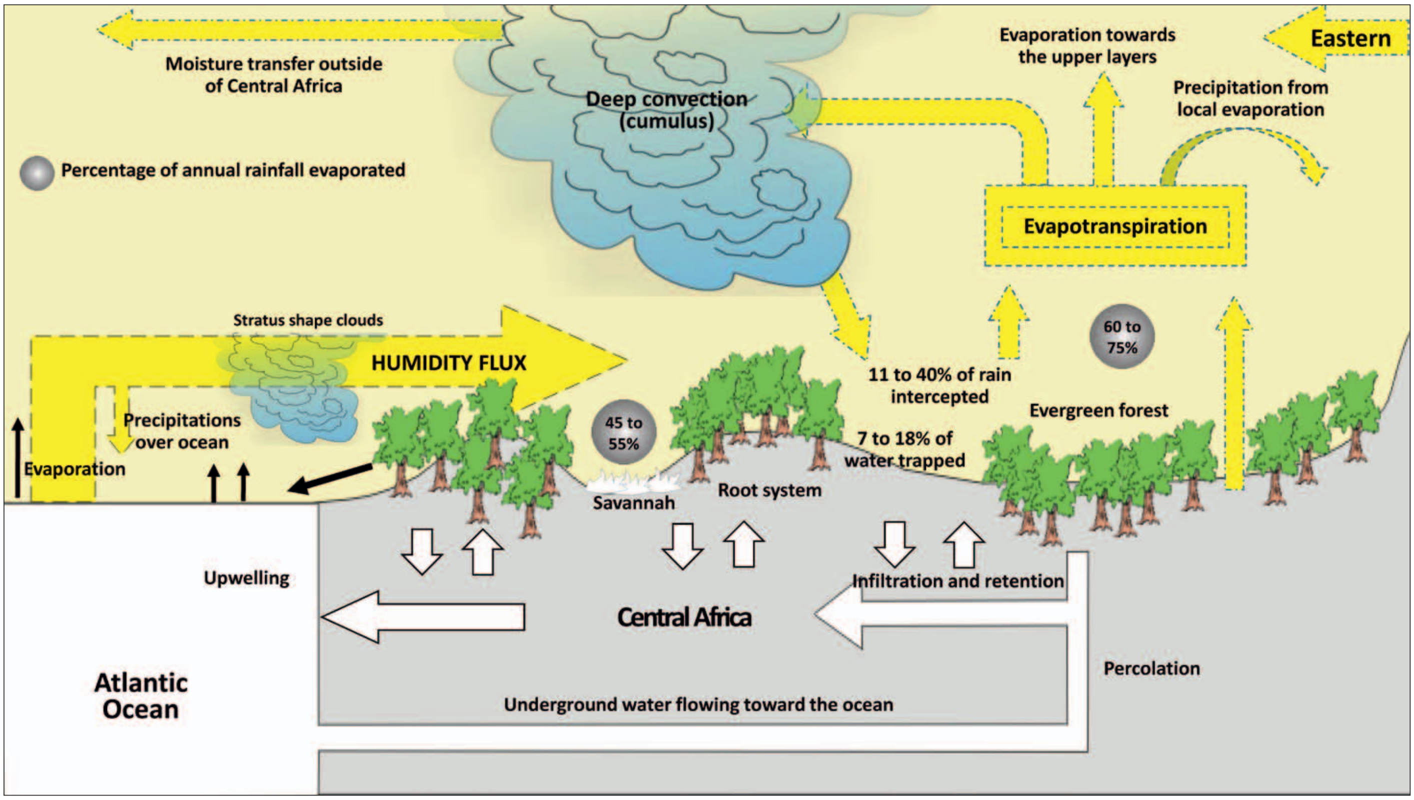


Figure 3.1 : Main interactions between water cycle and ocean-atmosphere-forest interface
Source : Bigot, 1997

1997). The rainfall associated with these convective systems depends then not only on the monsoon flow but also on the recycling of moisture by the forest (Cadet and Nnoli, 1987).

The forest system is both a receiver of precipitation (especially monsoon rains) ; and a generator of rainfall by means of evapotranspiration and fine scale processes (Bigot, 1997). It injects back in the atmosphere the equivalent of more than 50 % of the annual precipitation. Also, forests can reduce surface runoff and improve soil infiltration and fertility, which lead to increased soil moisture storage (Jose, 2009).

2.2 History of vegetation in relation to climate in a former time

This part of the text is largely inspired by the excellent publication of Mahé *et al.*, 2004.

The history of dense forests and their dynamics can be reconstituted by the study of fossils such as pollens or, much rarer, wood or carbon fossils, within specific disciplines such as palynology, paleo-botany or anthracology.

Thanks to recent advances in the area of paleo-ecology it has been shown that dense forests, such as those in Africa, have undergone profound changes in response to global climatic changes.

The end of Cretaceous, around 120 million years BP, marks a period of floristic conversion of tropical forests. Indeed, dominant gymnosperms plant forms, were replaced in favor of angiosperms plant forms. Since that time, the African dense tropical forests are almost entirely made up of angiosperms. At first, African dense forests were characterized by a great number of palm trees that became relatively rare and around 40 million years BP (upper Eocene), the floristic composition of these forests began to resemble their current state (Maley, 1996).

The irregularity of data in space and time makes it difficult to propose a very precise distribution scheme for the various types of ecosystems in forests of the past. Nevertheless, the major variations in tropical forests can be interpreted in a global context of temperature variations and in particular, of cooling phases (Maley, 1996). Not surprisingly, the forest extension phases were associated with humid period. Dryer periods had a direct impact on the vegetation which opened and dried out, resulting in forest regression and savanna expansion. Progressively, a pattern of seasonal climates alternating from dry to humid seasons emerged.

Till the beginning of the quaternary era (around 2.5 million years BP), there was a succession of contrasted dry and humid climates. These oscillations became less strong with a smoother impact on the vegetation.

Box 3.2: *Driving factors of the forest cover during the ice age and interglacial period*

The ice ages controlled the water level of the ocean; extension of the polar ice caps due to more frozen water at the poles results in a decrease of the sea level (for example, the sea level was lower by 120 m around the year 18,000 BP, during the last glacial maximum). This entailed a concurrent change in the amount of evaporating water surface. At the same time, global temperatures fell. This synchronous variation of lower water surface and lower temperature leads to a decrease of the quantity of water vapor in the air and therefore to a decrease of precipitation. On the continents, the resulting decrease in rainfall leads to a regression of forests and accordingly to an expansion of the savannas and open areas.

During interglacial period, the inverse phenomena, when polar ice caps melt combined with a general increase of temperature, leads to an increase of the sea level. The evaporation then increases. Combined with an increase of evapotranspiration by the vegetation, the quantity of water vapor in the air increases also and leads to more precipitation. On the continents, the resulting increase in rainfall leads to an expansion of forests and accordingly to a regression of the savannas and open areas.

For example, the maximum extension of the African forest seems to have been synchronous with a sudden rise in the sea surface temperatures of the Gulf of Guinea (Maley, 1997). Monsoons pick up moisture from the eastern Atlantic and this rise in water temperature has the effect to sharply increase the water vapor pressure and ultimately increase rainfall in the neighboring continent.

Photo 3.3: A key factor for the development of forests, is the amount of light reaching the different strata

The period between 2.5 million and 20,000 years BP known as the ice age and interglacial periods began with an arid phase and was marked by a significant expansion of savannas. Then came a progressive increase in the magnitude of glacial variation, marked by two principle phases: the first occurred between 2.5 million and 800,000 years BP, and was characterized by ice age/interglacial cycles of about 40,000 years; the second from 800,000 years BP to the current era and is characterized by dominant cycles of about 100,000 years.

Data shows that between 70,000 and 40,000 years BP, this region was relatively dry. At the global level, the maximum cooling period occurred between 20,000 and 15,000 years BP. As a consequence, monsoons were dramatically reduced which entailed a severe reduction of forests areas. Such reductions resulted in nothing more than a series of isolated forested areas, not far from the coast of the Gulf of Guinea and some others, near the center of the Congo Basin (riverine forests), and at the foot of the mountains of the African Rift (Maley, 1996, 1997).

From 15,000 years BP started the last expansion phase of forests that reached its optimum around 9,500 years BP of the last glaciation cycle. This corresponded to the warmest climatic phases in which ice masses of both polar ice caps were reduced. But there has been a major interruption around 2,800 years BP in southern Cameroon and western Congo (Maley and Brenac, 1998 ; Maley *et al.*, 2000 ; Vincens *et al.*, 2000). Extremely dry conditions were present in these regions between 2,800 and 2,000 years BP, facilitating the expansion of savannas and open spaces. This particular climatic phase appears to have resulted from an accentuation of the seasonality due to a shortening of the annual rainy season (Maley, 1997).

3. Impact of climate variation on vegetation

Changes of the forest cover can be related to climatic variations in the long-term (Sultan *et al.*, 2001 ; Mahé *et al.*, 2005), but at time scales that are much longer than what is observed since some decades in the regime variability of African Equatorial rivers. Climatic variability is defined as being the distribution of climatic elements around their average values calculated over 30 years ; this natural variability is an intrinsic character of climate (Janicot, 1995).

The space-time variability of climate principally depends on the interaction between the surface conditions (temperature, albedo, humidity) and the atmosphere : linkage manifested by wind pressure and sensible and latent heat flows.

3.1 Vulnerability framework

Vulnerability can be defined as “the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes”. The vulnerability framework [V= f (E, S, A)] considers vulnerability (V) as a function (f) of exposure (E), sensitivity (S), and adaptation (A). The function can also be applied to the forest sector (Locatelli *et al.*, 2008, see : Figure 3.2).

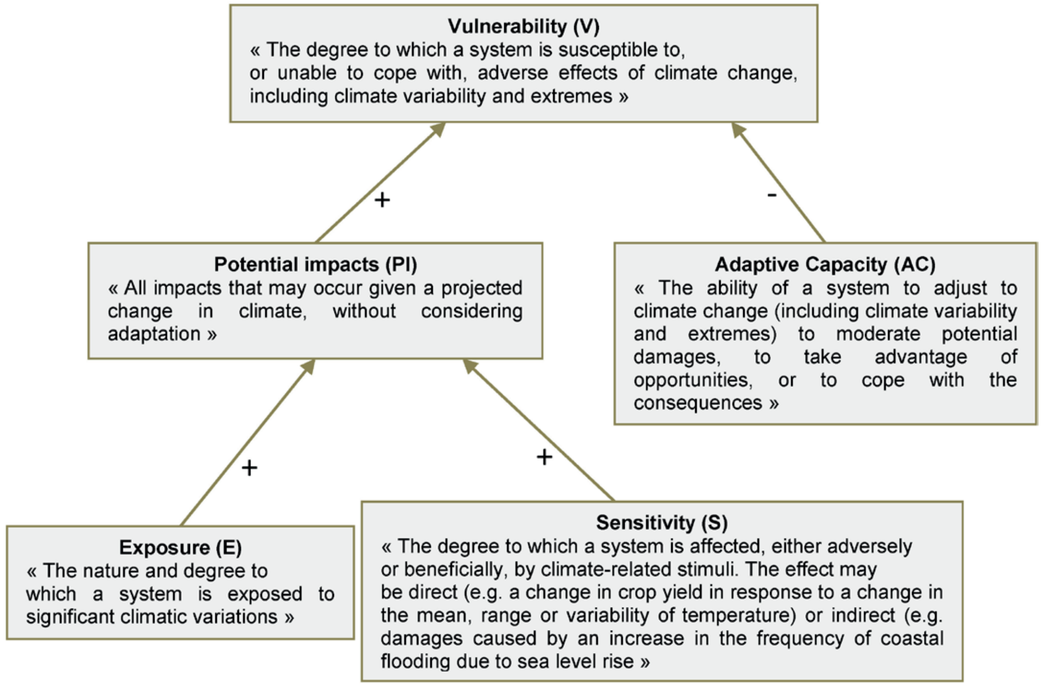


Figure 3.2: The components of vulnerability (definitions are from IPCC: McCarthy et al., 2001). The signs under the arrows mean that high exposure, high sensitivity and low adaptive capacity induce high vulnerability.

Adapted from Locatelli et al., 2008.

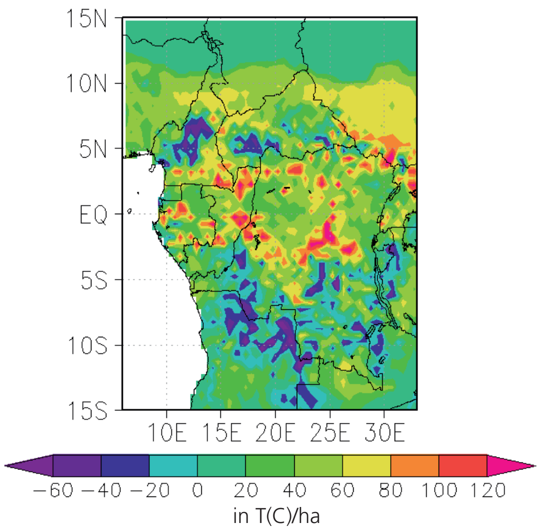
3.2 Direct impacts

Climate change is expected to have a range of impacts on forest ecosystems. However, the effects of CO_2 and temperature on tropical forest growth are not yet fully understood. Generally it appears that higher atmospheric CO_2 concentrations might increase forest growth and carbon capture. Higher temperatures, however, might have negative impacts on forest growth and reduce the amount of carbon in the forests (Jupp *et al.*, 2010). Also, climate change can affect the forest reproduction, and it can cause their decline.

Photo 3.4: Unlike the forest, fossil fuel combustion is not renewable

Possible future trends in forest response to climate evolution

The impact analyses show that the Congo Basin is unlikely to see a decline in forest growth as is sometimes predicted for the Amazon Basin as a result of climate change. Instead, there could be a moderate increase in ecosystem carbon, including vegetation and soil carbon (Figure 3.3). Depending on how the climate will change, there could also be a shift in the ecosystems' land cover between forest and savanna. Based on the analysis, the most likely future scenario involves a moderate expansion of evergreen forests into savannas and grasslands to the North and the South of the current forest-savanna-transition zone. There is a large uncertainty range in the model assessments, highlighting the importance of collecting new data to further narrow the prediction ranges (e.g., biomass in the central Congo Basin and responses of forests to changing climate and CO_2 concentrations).



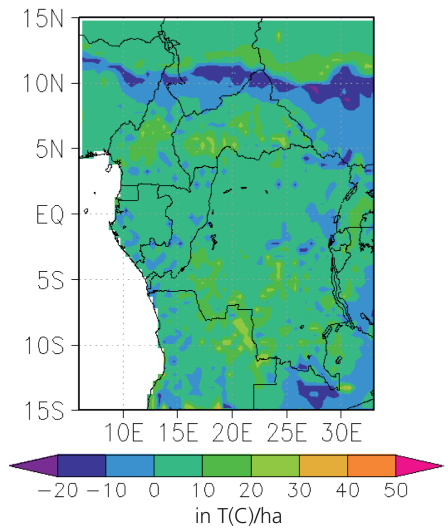


Figure 3.3: The projection of change towards the end of this century (mean of the period 2071-2100 compared to the mean of the period 1961-1990) under a high emission scenario. In the left panel, changes in potential vegetation carbon are shown, and in the right panel, changes in potential soil carbon are shown. The sum of these two panels indicates the changes in total ecosystem carbon. Changes in potential vegetation and soil carbon are calculated using the Lund-Potsdam-Jena-managed lands (LPJ-ml) model in combination with a single climate model (ECHAM5).

Source: CSC, 2013

3.3 Indirect impacts

The effects of climate change are often indirect, for example by affecting the frequency of fires or modifying the behavior of pests and diseases. During the "El Niño" years of 1983, 1987, and 1997, fires were particularly destructive in southeastern Cameroon. The effects of climate change can accelerate biodiversity loss through the disappearance of species or by reducing the resilience of severely disrupted ecosystems. The climate can have immediate and sustained effects on hydrology (Li *et al.*, 2007), that can have itself an impact on vegetation.

The impact of climate change on water regimes has already affected vegetation. Prior to the considerable drop in water levels of Lake Chad, vegetation in the north of the Congo Basin was mainly composed of *Phragmites*, *Cyperus papyrus*, *Vossia, Typha, Potamogeton* and *Ceratophyllum*. The drop in the lake's water level led to important vegetation changes and by 1976, the bulk of the vegetation was no longer constituted of *Vossia* and *Aeschynomene sp.* (Olivry, 1986). Changes in aquatic vegetation were also observed in the Logone flood plain in northern Cameroon where flooding had declined in the

1970s following the upstream construction of a dam. Certain plant species characteristic of flood areas, such as *Vetiveria nigritana* and *Echinochloa pyramidalis,* were replaced by other species, notably *Sorghum arundinaceum* (Scholte *et al.,* 2000 ; Scholte, 2007).

4. Impact of deforestation on climate characteristics (temperature, rainfall)

Box 3.3 : *Latent and sensible heat*

Latent and sensible heat are released or absorbed in the atmosphere. Latent heat ("Latent" means "hidden") is related to changes in phase between liquids, gases, and solids. It is generally used interchangeably with its mass equivalent (evapotranspiration) in plants. Latent heat is absorbed when a substance changes from solid to liquid and from liquid to vapor, and it is released when the vapor condenses into liquid, and when the liquid freezes into solid.

Sensible heat is related to changes in temperature of a gas or object with no change in phase.

Water vapor is a greenhouse gas located in the atmosphere and a very important component of cloud formation. Clouds form when moist, warm rising air cools and expands in the atmosphere. If the air is dry, or unsaturated, clouds are not likely to form because there is minimal water vapor in the air. If the air is moist, or saturated, the water vapor will condense to form tiny water droplets which are the basis of clouds. When these gas molecules condense into liquid drops, latent heat is released into the atmosphere which warms the air surrounding the molecule. This helps to add instability in the atmosphere as the warm air surrounding the molecule decreases in density and rises. Warm air is less dense than cold air because molecules in warm air move around much faster and move further apart.

Source : https ://www.nc-climate.ncsu.edu/edu/k12/.lsheat

Photo 3.5 : Construction of a base camp of a logging company

The surface conditions, especially the plant cover of dense rainforests and the upper layer of oceans have a significant effect on the atmospheric water cycle and also on the vertical movements within the tropical atmosphere.

Deforestation can significantly alter the surface water and energy balance in multiple ways and thus affect atmospheric temperatures and moisture content, atmospheric boundary layer development, and weather and climate processes at continental scales (Niyogi *et al.*, 2009).

Forest conversion to agriculture and other land uses increases the portion of bare ground exposed to the sun's rays and therefore increases albedo which lowers incoming solar radiation absorbed by the surface and energy available for sensible and latent heat flux.

Considering these mechanisms, the role of deforestation, particularly in the Congo Basin region, has received relatively little attention in understanding African climate and climate change.

To date, research in the Congo Basin region has primarily focused on "global" drivers of climate and future change, such as warming sea surface temperatures and rising CO_2 emissions, and has ignored deforestation and other land drivers, because land-atmosphere coupling is considered a highly localized phenomenon (Koster *et al.*, 2004).

In addition, several uncertainties and bias in the models used to simulate these processes may obscure their importance (Pielke *et al.*, 2007). These uncertainties and bias include: (i) the spatial resolution at which processes are modeled is too coarse to capture the fine scale spatial structure of deforestation (Brunsell and Anderson, 2011); (ii) groundwater is typically ignored or simulated using simple "slab" soil models that do not sufficiently estimate soil saturation or its influence on moisture feedbacks (Ferguson and Maxwell, 2011); (iii) sensible heat and latent heat is difficult to partition (de Noblet-Ducoudré *et al.*, 2012); (iv) studies simulate processes using only one global climate model coupled to a land surface model instead of a multi-model ensemble; and (v) deforestation is assumed a linear or static process (Pielke *et al.*, 2011).

Thus the sensitivity of the tropical climate to forest conversion remains open to debate.

At the regional level, the deforestation impact on climate is assessed more with regards to carbon emission, temperature increase, and rainfall balance. Deforestation impact on local climate is more studied through characteristics such as flux of energy, moisture, evapotranspiration, soil properties and albedo. Currently, there is a growing body of evidence showing the impact of deforestation on local climate in the Congo Basin, while its impact on regional (African) climate is less clear and global teleconnections unknown (Lawrence and Vandecar, 2015).

4.1 Deforestation and its effects on local climate

The impact of the forest clearance on the rainfall/runoff relationships seems to be dependent on the type of climate/vegetation system.

In Sahelo-Sudanian areas, the forest clearance, associated with an increase of agricultural activities, rapidly induces a destructuration of the top layer of the soil in which infiltration decreases, and runoff coefficients increase (Mahé and Paturel, 2009; Descroix *et al.*, 2010). But in more humid tropical and equatorial areas such a correspondence is not observed.

The reduction of the forest cover has therefore a direct impact toward the increase of runoff in Sahelian basins. In Equatorial areas, although the river regimes have been well studied, we still have to study the possible link between changes of the forest cover and the intraseasonal changes of the equatorial river regimes.

ORSTOM (IRD) hydrologists have studied the river regimes of many rivers for decades since the 1950s. Data are gathered in the SIEREM information system (Boyer *et al.*, 2006) (http://www.hydrosciences.org/sierem/) and in the Hybam observatory (http://www.ore-hybam.org) for the Congo catchment. These data are used to study the variability of the river regimes, which can be linked to rainfall changes, but could also be related to changes in the forest cover. Studies about the impact of forest cut on

Photo 3.6: If the forest succeeds to the forest in the process of charcoal production, then the carbon balance would be close to zero.

river regimes are not numerous, and often relate to very small experimental basins (Fritsch, 1990).

In equatorial humid areas the major impact of the forest conversion is to reduce the local evapotranspiration, thus reducing the total amount of available water vapour through local recycling for monsoon rainfall. Due to lack of direct measurements, it is very difficult to estimate the impacts of a massive forest conversion on the climate dynamics as well as on evapotranspiration.

The loss of forest cover triggers an increase in albedo and decrease in available energy, leading to further declines in latent heat in favor of sensible heating. Cloud cover does not change significantly, but downward longwave radiation does increase due to the warming of the atmosphere from increased sensible heating, which offsets some loss in net radiation due to albedo.

Deforestation can also decrease rainfall by weakening direct coupling, local coupling, and indirect recycling (Makarieva *et al.*, 2013).

Direct coupling is the process by which rainfall is recycled back into the air via evaporation from bare soil and transpiration through plant stomata (evapotranspiration – mass equivalent of latent heat). With fewer trees, there is less moisture available for this process.

With local coupling, deforestation decreases surface roughness, which can suppress daytime boundary-layer turbulence and instability important for cloud development (increased downward longwave radiation) and rainfall (Santanello *et al.*, 2007).

Finally, with indirect recycling, large moist air masses from the ocean, which would otherwise be buffered against drying due to evapotranspiration from forests, lose moisture necessary for storm development downwind.

4.2 Impact of deforestation at the regional level

Multiple climate and land scenarios indicate that deforestation in the region could lead to warming between 2 and 4°C due to a decrease in evapotranspiration (latent heat) and shade, combined with increased forcing from lower greenhouse gas sequestration (Figure 3.4) (Akkermans *et al.*, 2014 ; Nogherotto *et al.*, 2013). The change in temperature is less severe on the Atlantic side and eastern border of the Democratic Republic of Congo, because latent heat is considerably higher in these areas and thus less sensitive to temperature changes. Direct and local moisture coupling under the scenarios are also expected to weaken, which could lead to as much as a 5 to 10 % decrease in rainfall over much of the region (Figure 3.5).

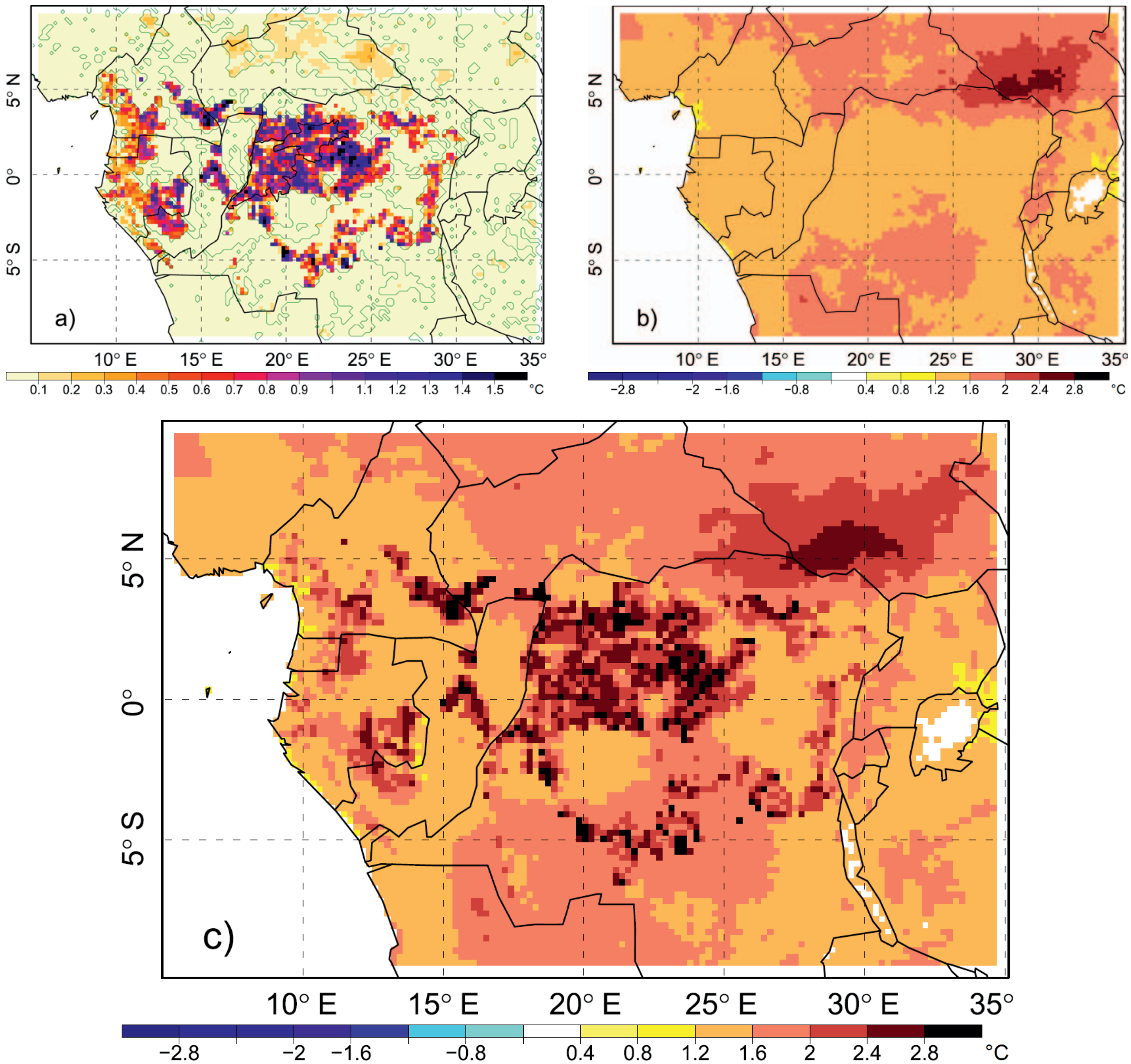


Figure 3.4 : Mean temperature change (°C) due to the succession of forests in the Congo Basin region to agriculture and other land uses from 2041-2060 directly from modifications due to the water and energy balance (a) ; indirectly from increased greenhouse gas forcing (b) ; and (a) and (b) combined. Significance on the 1% level is indicated by the green contours in (a).

Source : Akkermans et al. (2014).

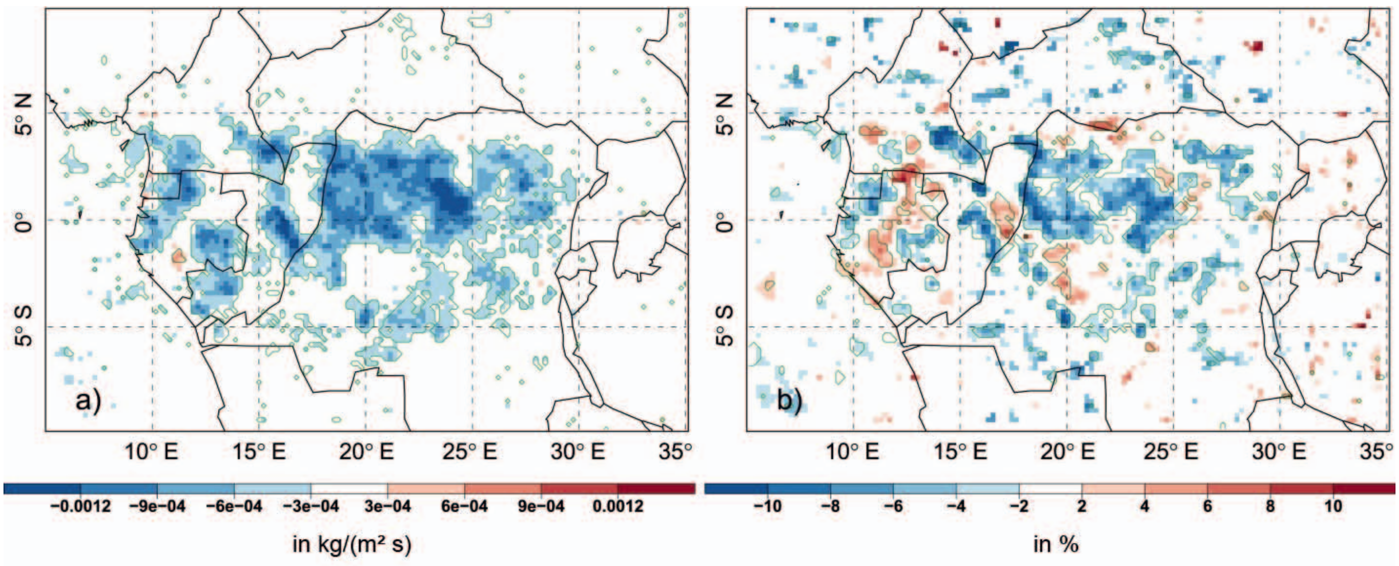


Figure 3.5 : (a) Upward convective mass flux density change at cloud-base height in absolute terms[16] (kg m^{-2} s^{-1}) and (b) changes in rainfall due to the succession of forests in the Congo Basin region to agriculture and other land uses from 2041-2060 (in %).

Source : Akkermans et al. (2014).

The increase in surface temperatures and decrease in rainfall will essentially intensify convection (low) over the Congo Basin region, but it will be warmer and less humid than now. The low is expected to intensify the West African Monsoon (WAM), which will lead to increased rainfall in more distant locations, such as the Sahel and Ethiopian Highlands (Guinea coast). However, remote sensing based rainfall (Spracklen *et al.*, 2012) and isotopic (Levin *et al.*, 2009) data provide an alternative scenario. Moisture in South Sudan and the Ethiopian highlands (and less so in the western Sahel) during the WAM originates from the Atlantic Ocean, but must pass over the Congo Basin region first. Forest cover and evapotranspiration in the region could act as a buffer against moisture loss as the warm wet air masses of WAM move onshore (indirect recycling). If the forests were not there or severely degraded, the air masses would dry out, leaving little moisture for storm development and rainfall over much of the Sahel and Ethiopian Highlands during the critical WAM rain season in the future.

16 This unit corresponds to the displacement of a fluid, of density ρ in kg/m^3 (in this case the air) at a speed v in m/s.