Africa: Greening of the Sahara

Africa: a hot spot of non-linear atmosphere-vegetation interaction

In many classical considerations about climate, its interaction with the biosphere played a dominant role. For example, Köppen (1936) described vegetation as “crystallized, visible climate” and referred to it as an indicator of climate much more accurate than our instruments. However until a few decades ago, many climate researchers doubted that vegetation could have a strong and significant impact on global climate changes besides those impacts related to modification of carbon storage and hence atmospheric CO_2 concentration. Today, we are convinced that in some regions, which we call “hot spots”, vegetation also affects continent-scale atmospheric motion - North Africa is an excellent example of such a hot spot.

Charney (1975) formulated a theory of biogeophysical interaction in subtropical deserts. He argued that high albedo of sand deserts tends to stabilize deserts by changing the radiative budget above deserts thereby shifting large-scale atmospheric flow. Later on numerical models and theory (Brovkin et al., 1998) indicate that the interaction between atmosphere and land cover in North Africa is highly non-linear. When initialized with different land surface conditions, an atmosphere - vegetation model can yield different solutions (Claussen, 1997). With present-day conditions or with deserts covering all continents, the model predicts the present-day climate. But when continents are covered with vegetation initially, the model simulates a more humid climate with a Sahara greener than today. The qualitative feature of multiple solutions emerging mainly in the subtropical North Africa has been corroborated with completely different atmosphere-vegetation models (Wang and Eltahir, 2000; Zeng and Neelin, 2000). Moreover, the existence of multiple equilibria has been used to interpret decadal rainfall variability in the Sahel (Wang and Eltahir, 2000).

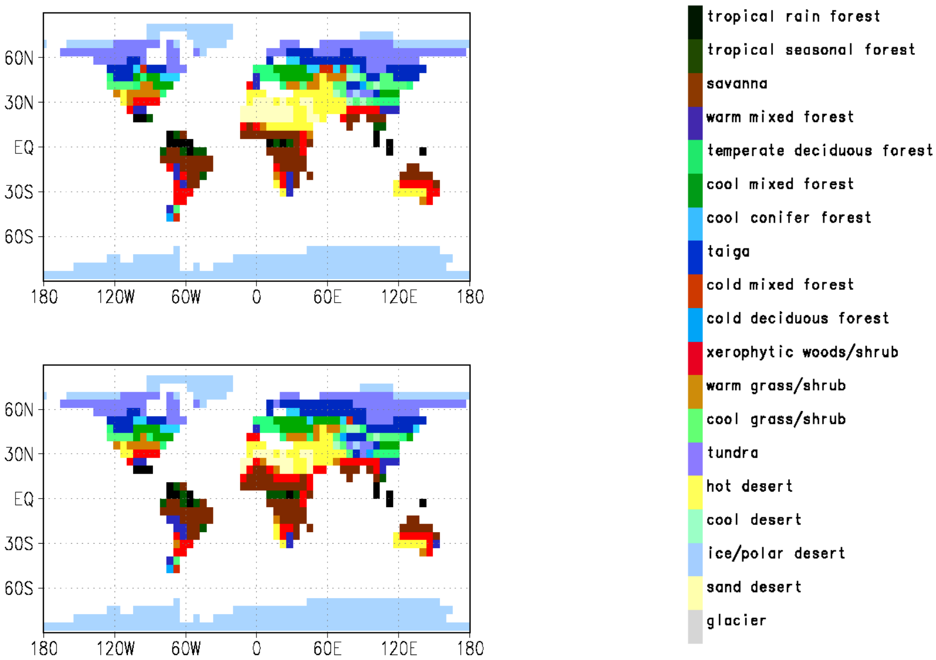

Fig. 1: Equilibrium solutions of an atmosphere - vegetation model for present-day ocean temperatures and insolation (Claussen, 1997) shown in terms of global biome patterns.

The African wet period

A “green Sahara” is not just a model artifact. Palaeoclimatic reconstructions indicate that during the so-called Holocene climatic optimum some 9 - 6 thousand years ago, the summer in the Northern Hemisphere was warmer than today. North African monsoon was stronger than today according to lake level reconstructions (Yu and Harrison, 1996) and estimates of aeolian dust fluxes (deMenocal et al., 2000), for example. Moreover, palaeobotanic data (Jolly et al., 1998) reveal that the Sahel reached at least as far north as 23^{o}N. (The present boundary extends up to 18^{o}N.) Hence, there is an overall consensus that during the Holocene optimum, the Sahara was much greener than today (e.g., Prentice et al., 2000).

The greening was tentatively attributed to changes in orbital forcing (e.g., Kutzbach and Guetter 1986) that amplified the North African summer monsoon. However, orbital forcing of palaeo monsoon alone did not seem to be strong enough to explain wide-spread greening (Joussaume et al., 1999). Models which include atmosphere-vegetation interaction yielded a stronger greening (Claussen and Gayler, 1997; Doherty et al., 2000). It has also been suggested that the changes in the ocean could have contributed to a stronger summer monsoon (Braconnot et al., 2000), but a complete factor separation analysis undertaken by Ganopolski et al. (1998) demonstrates the overwhelming role of interactive dynamic vegetation.

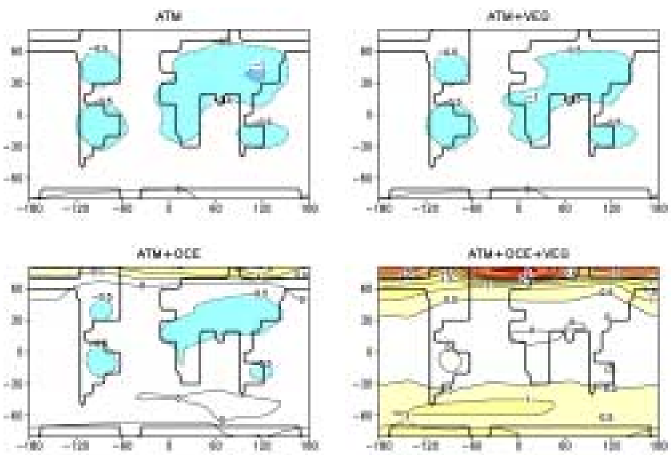

Fig. 2: Differences in near-surface temperatures during northern hemisphere winter (December, January, February) between mid-Holocene climate and present-day climate simulated by Ganopolski et al. (1998). The authors used different model configurations: the atmosphere-only model (labelled ATM), the atmosphere-ocean model (ATM + OCE), the atmosphere-vegetation model (ATM + VEG) and the fully coupled model (ATM + OCE + VEG). In ATM, ATM + OCE, and ATM + VEG, present-day land-surface and ocean-surface conditions - depending on the model configuration - are used

Abrupt changes in North Africa

Until some 6000 years ago, the Sahara was much greener than today; how did the Sahara become what it looks like today? Alexander von Humboldt (1849) imagined the aridification of North Africa to be caused by an oceanic impact. He argued that somewhere in the “dark past”, the subtropical Atlantic gyre was much stronger and flooded the Sahara, thereby washing away vegetation and fertile soil. By contrast, Claussen et al. (1999) suggested that vegetation itself strongly affected the change from a green North Africa to present-day Sahara. They have analysed the transient structures in global vegetation pattern and atmospheric characteristics using the coupled atmosphere-ocean-vegetation model of Ganopolski et al. (1998). Their simulations show that subtle changes in orbital forcing triggered changes in North African climate which were than strongly amplified by biogeophysical feedbacks in this region. The abrupt aridification - abrupt in comparison with the subtle change in orbital forcing - is a regional effect caused by the non-linearity of the atmosphere-vegetation feedback, the timing of it turned out to depend, however, on global processes such as continent-scale meridional temperature gradients which are governed, besides other processes, also by changes in boreal vegetation and Arctic sea ice.

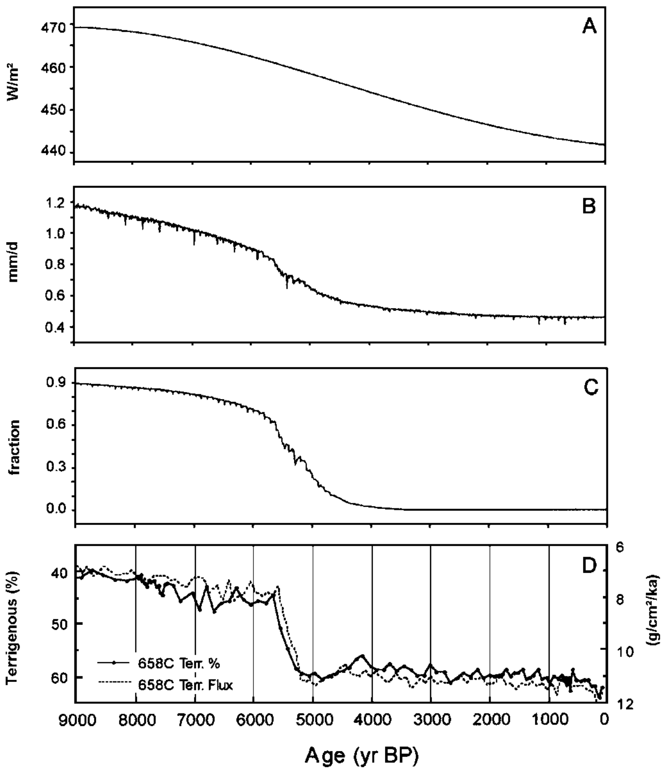

Fig. 3: Simulation of transient development of precipitation (Part B) and vegetation fraction in the Sahara (Part C) as response to changes in summer insolation on the Northern Hemisphere (Part A). These results obtained by Claussen et al. (1999) are compared with data of terrigenous material and estimated flux of material in North Atlantic cores off the North African coast (Part D). This figure is taken with modifications from deMenocal et al. (2000)

Will North Africa become green again in the near future?

Petit-Maire (1990) asked whether greenhouse will green the Sahara, thereby hypothesizing that in increase in atmospheric CO_2 concentrations owing to fossil fuel burning would lead to a warmer climate which in some respect could resemble the Holocene climate optimum with its greener Sahara.

Most climate models reveal an increase of precipitation in the African tropics and the Sudan and a decrease in the subtropics, if atmospheric CO_2 concentration are prescribed to continuously increase. For today's Sahara, however, there seems to be no unequivocal result. Some models show an increase in precipitation, other a decrease. On the other hand, if precipitation were to increase over today's Sahara, then we can expect that it will be amplified by the atmosphere-vegetation feedback. Indeed, sensitivity tests in progress (Claussen et al., submitted) suggest that some expansion of vegetation into today's Sahara is theoretically possible, if atmospheric CO_2 concentration increases well above pre-industrial values and if vegetation growth is not disturbed by grazing, for example. Depending on the rate of changes in atmospheric CO_2 concentrations the rate of greening can be fast, up to 1/10th of the Saharan area per decades. Such a greening, on the other hand, does not imply that the mid-Holocene climate optimum with its strong reduction of North African deserts can be considered a direct analogue for future greenhouse-gas induced climate change. According to the model study, not only the global pattern of climate change between the mid-Holocene model experiments and the greenhouse-gas sensitivity experiments differ, but also the relative of role mechanisms which lead to a greener Sahara. Moreover, the amplitude of simulated vegetation cover changes in North Africa is less than estimated for mid-Holocene climate.

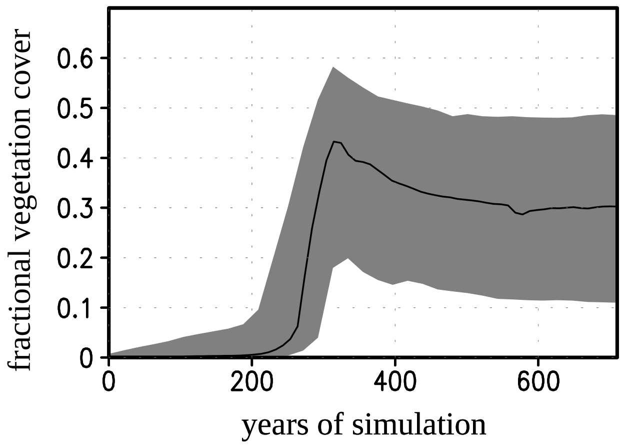

Fig. 4: Increase in fractional vegetation cover in the Sahara as a response to an increase in atmospheric CO_2 concentration simulated by an Earth system model of intermediate complexity. During the first 200 years of simulation, CO_2 changes are taken from reconstruction and measurements for the period of 1800 until 2000. Thereafter, CO_2 is prescribed to increase by 1% per year until a value of 1000 ppmv is reached, then the CO_2 concentration is kept constant at 1000 ppmv. The full line indicates a best guess. The shaded area indicate the uncertainty range owing to changes in the parameterization of vegetation processes in the model.

Outlook

North Africa is a fascinating example of a hot spot of atmosphere-vegetation interaction. Theory and model experiments suggest that this interaction is highly non-linear. It presumably affects Sahelian rainfall variability. Moreover, palaeoclimatic changes cannot be fully understood, when atmosphere-vegetation interaction is ignored. Whether North Africa will become greener again, as our stone-age ancestors have witnessed, cannot be forecasted because of model uncertainty and because socioeconomic boundary conditions are not known for the next centuries. There is some theoretical evidence that the Sahara could become greener, but direct anthropogenic land-cover change in North Africa is likely to be much more important than greenhouse-gas induced climate change in this respect.

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