Positive and negative feedbacks in the vegetation impact on the Sahel Drought

FRED KUCHARSKI[1] & NING ZENG[2]

[1] Abdus Salam International Centre for Theoretical Physics, Earth System Physics Section
[2] Department of Atmospheric and Oceanic Science, University of Maryland
kucharsk@ictp.it

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Abstract
In this contribution, the vegetation feedback mechanisms on the Sahel drought are revisited and further analysed using the intermediate complexity Atmospheric General Circulation model SPEEDY coupled to the VEGAS dynamic vegetation model. It is found that the albedo feedback provides a strongly positive feedback to the atmosphere-vegetation system. The albedo increase leads to a reduction in net surface radiation that is mainly compensated by reduced evaporation (latent heat loss), providing one major source of the total rainfall response. Another positive feedback is provided by the pressure response to the reduced atmospheric heating in the Sahel region that leads to a high pressure in the Saharan region, thus weakening the Saharan heat low and being favourable for diverging north-easterly wind anomalies in the Sahel region. The major negative feedback is provided by the vegetation impact on evaporation, which limits the response in soil wetness and is thus stabilizing the coupled atmosphere-vegetation system.
Key words: Sahel drought, dynamic vegetation, feedback mechanisms.

Mecanismos de realimentación positivos y negativos en el impacto de la vegetación en la sequía del Sahel

Resumen
En esta contribución se revisitan y analizan los mecanismos de realimentación de la vegetación en relación a la sequía en el Sahel, utilizando el Modelo de Circulación General de la Atmósfera SPEEDY acoplado al modelo de vegetación dinámica VEGAS. Se ha encontrado que el mecanismo de realimentación del albedo produce una fuerte realimentación positive al sistema atmósfera-vegetación. El aumento de albedo produce una reducción en la radiación neta superficial que es compensada principalmente por una reducción de la evaporación (pérdida de calor latente), siendo una fuente principal de la respuesta total de la precipitación. Otro mecanismo de realimentación positivo lo proporciona la respuesta de la presión a la reducción del calentamiento atmosférico en la región del Sahel, que da lugar a una alta presión en la región del Sahara, debilitando la baja térmica sahariana y favoreciendo anomalías de viento del noreste y divergencia en el Sahel. El feedback negativo más importante es el impacto de la vegetación en la evaporación, que limita la respuesta de la humedad del suelo estabilizando el sistema acoplado atmósfera-vegetación.
Palabras clave: Sequía en el Sahel, vegetación dinámica, mecanismos de realimentación.

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1. Introduction

The physical mechanism for the Sahel drought that peaked in the 1980s has been intensively investigated in the scientific literature over the last decades. The emerging picture is that oceanic forcing provides a major initial perturbation in rainfall that is enhanced by local land-surface feedbacks (Palmer 1986; Folland et al., 1986, 1991;.Rowell et al., 1995; Ward 1998; Giannini et al., 2003; Bader and Latif 2003; Zhang and Delworth 2006; Hagos and Cook 2008; Mohino et al., 2011; Zeng et al., 1999; Wang et al., 2004; Scaife et al., 2009; Kucharski et al., 2013a, and many others). The Sahel drought may be considered as part of a global tendency for monsoons to weaken in the second half of the 20th century, and the driving sea surface temperature (SST) pattern has contributions from the Atlantic Multidecadal Oscillation (AMO), Interdecadal Pacific Oscillation (IPO) and also from global warming (Zhou et al. 2008a, b; Mohino et al., 2011). The positive feedback from the land-surface is mainly related to the soil moisture and vegetation dynamics. Both decrease with reduced rainfall and may limit the local evaporation as source for the Sahel rainfall (Zeng et al., 1999). Other local mechanisms that have been proposed to have enhanced the Sahel drought are anthropogenic land use/land cover changes (Charney 1975; Charney et al., 1977; Xue and Shukla; Xue 1997; Zheng and Eltahier 1997; Claussen 1997, 1998; Clark et al. 2001; Pitman et al., 2009) and anthropogenic aerosol or dust (e.g. Yoshika et al., 2007). The physical mechanism how vegetation changes may influence rainfall is mainly due to changes in surface albedo (Charney 1975; Charney et al. 1997), although also a potential role of the vegetation in modifying directly the evaporation has been proposed (Zeng et al., 1999). The surface albedo in turn changes the energy flux absorbed, and thus the stability and convective activity.

Recently, Kucharski et al. (2013a), in the following referred to as K13, analysed the vegetation feedback on the Sahel drought in more details using large ensembles of simulations with the intermediate complexity Atmospheric General Circulation Model (AGCM) SPEEDY (or ICTPAGCM) coupled to the dynamic vegetation model VEGAS (UMD-ICTP). K13 confirmed the dominant role of the albedo in driving the positive vegetation feedback to the Sahel drought. However, they also suggested a negative feedback associated with the vegetation variations. K13 found that the response in rainfall is strongly increased when the direct evaporation dependence on vegetation cover is suppressed.

Thus the interpretation is that this dependence provides a negative feedback to the coupled atmosphere-vegetation system. This negative feedback related to the influence of vegetation cover on evaporation works as follows: If rainfall is reduced, then the equilibrium soil moisture and vegetation cover will be reduced. A reduction in vegetation leads to increased albedo. The albedo feedback reduces the net surface heating, which is mainly compensated by a reduction in latent heat release at the surface (reduced evaporation). This is established mainly by soil moisture and vegetation cover adjustment, both of which modify evaporation. If, on the other hand the evaporation dependence on vegetation cover is suppressed, an equilibrium can only be reached having an even lower soil moisture, which even further reduces vegetation cover. If the dependence of evaporation on vegetation cover is retained, then the soil moisture adjustment is limited and thus provides a negative feedback to the coupled atmosphere-vegetation system.

The aim of this contribution is to further analyse the positive albedo feedback and the negative feedback due to the dependence of evaporation on vegetation cover with idealized simulations using the UMD-ICTP model.

The paper is organized as follows: Section 2 presents the model and experimental set up, whereas the results are presented in Section 3. Finally, section 4 presents the summary and conclusions.

2. Model and Experimental set-up

The model used in the study is the UMD-ICTP presented in the Introduction. The model consists of the International Centre for Theoretical Physics AGCM (ICTPAGCM, Kucharski et al., 2013b), version 41, coupled to the dynamic vegetation model VEGAS (Zeng et al., 1999, 2000, 2005; Zeng 2003, 2007). For a detailed description, the reader is referred to the paper K13. In the current study the UMD-ICTP uses a spectral truncation at wavenumber 30 (about 3.75x3.75 horizontal resolution), and the AGCM has 8 vertical levels. The models performance in reproducing northern African monsoonal mean climate and vegetation has been demonstrated in K13. Although biases are present, the model is able to simulate the June-to-September (JJAS) mean rainfall and low-level winds reasonable well compared to observations and other models. Moreover, the JJAS mean vegetation cover is also simulated reasonably well compared to observations.

However, in the set-up used in this study, the vegetation cover is not dynamic, but prescribed in order to identify the positive and negative feedback mechanisms. We use the results from K13 to estimate vegetation cover and albedo changes during the Sahel drought, and prescribe these in the Atmospheric component of the UMD-ICTP. Soil moisture feedbacks are retained in the simulations. In K13 the simulated rainfall difference of a 20-member ensemble mean between the two periods 1980 to 1994 minus 1950 to 1964 shows a drying in the Sahel regions that has a similar structure to the observed one, but only about 60% of the observed magnitude. We have used the magnitudes of the corresponding vegetation cover and albedo changes from these simulations (see Fig. 9a and 9b in K13) in order to perform 2 idealized sensitivity experiments in addition to a control experiment:

In the experiment CNTRL we perform a 63-year long simulation with observed vegetation cover and albedo. The SSTs are climatological (that is monthly varying, but interannually constant), and derived like all other boundary conditions from the ERA Interim (Dee et al., 2011) for the period 1979 to 2008. The first 2 years of the simulation are treated as spin-up, and the last 61 years are used for analysis.

In the experiment ALB_VEG we prescribe vegetation cover to reduce and the albedo to increase by 5% in the Sahel region (19W to 35 E, 6 to 17N) with respect to CNTRL, otherwise the simulation is identical to CNTRL.

In Experiment ALB, only a 5% increase of the albedo with respect to CNTRL is prescribed, otherwise the simulation is identical to CNTRL.

Fig. 1 shows the prescribed albedo and vegetation perturbation for ALB_VEG. Note that in Fig. 1b there are regions close to the desert with less than 5% change, because the vegetation cover approaches zero there in the climatological mean.

The aim of ALB_VEG is to investigate the effect of both albedo and vegetation changes of the simulated rainfall, whereas ALB is to investigate just the effect of albedo changes. In the AGCM, the albedo influences the climate through the amount of solar radiation reflected at the surface, whereas the vegetation cover influence climate only in the calculation of the evaporation from the root zone, which is proportional to the vegetation cover.

3. Results

All results presented are based on the differences between the experiments averaged for the JJAS season over the 61-year simulation periods. The response in rainfall in the experiments ALB_VEG and ALB with respect to CNTRL are rather similar (Fig. 2a, 2b), and show a strong drying in the Sahel region exceeding 1 mm/day in some parts.

This result is confirming the dominant role of the albedo mechanism for the rainfall response. We further analyse the mechanism by calculating the net surface radiation change (Fig. 3a 3c), and evaporation changes (Fig. 3b, 3d), respectively. As expected, the increased surface albedo reduces the net surface radiation, which is mainly compensated by decreased evaporation. Note that the near-zero heat capacity of the land surface implies a near zero energy flux into the surface and therefore a strong link between net radiation and evaporation.

This decreased evaporation in the Sahel region is a direct mechanism to reduce rainfall, given that the total rainfall is the sum of evaporation and vertically integrated moisture flux convergence (Peixoto and Oort, 1983). However, the fact that the evaporation changes are smaller than the rainfall changes indicate that also the moisture flux component is an important contribution to the Sahel drying. This means that the dynamical response to the reduced Sahelian heating also provides a positive feedback to the drying. Indeed, Fig 4 shows the surface pressure and 925 hPa wind responses for ALB_VEG with respect to CNTRL (the response in ALB is very similar and therefore not shown), which indicate a positive pressure anomaly just to the north of Sahel around 20N and north easterly diverging winds in the Sahel region that are leading to moisture flux divergence.

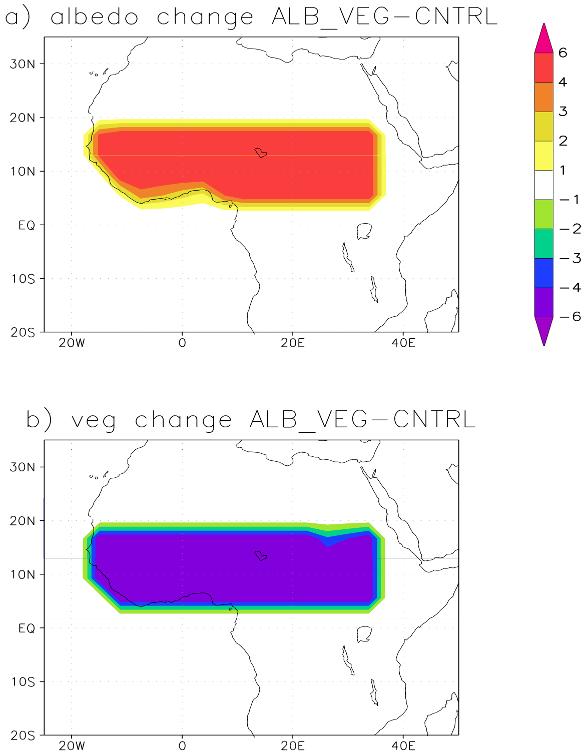

Fig. 1. a) Prescribed albedo and b) vegetation cover change in experiment ALB_VEG with respect to CNTRL. Units are %.

The responses in ALB_VEG and ALB with respect to CNTRL are very similar. On the other hand in K13 it was shown that in the coupled atmosphere-vegetation simulations the response was much stronger when the vegetation change impact on evaporation was suppressed. Therefore the negative (stabilizing) feedback provided by the influence of vegetation on evaporation is only present in case of the coupling of the AGCM to the dynamic vegetation component.

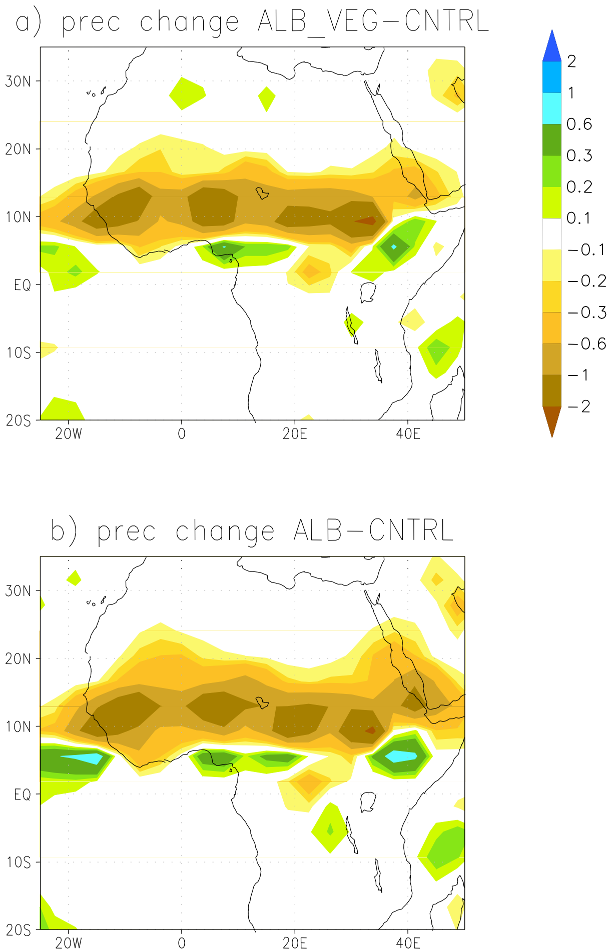

Fig. 2. Precipitation response for JJAS a) ALB_VEG-CNTRL, b) ALB-CNTRL. Units are mm/day.

A main driver of the vegetation cover is the soil moisture, and this information is passed from the atmospheric land-surface model to the vegetation model. Fig. 5a and 5b show the total soil wetness change in ALB_VEG and ALB with respect to CNTRL respectively.

As expected the soil wetness is decreasing in the Sahel region in both experiments with respect to the CNTRL. This is due the reduced rainfall. However, even though ALB_VEG and ALB show very similar rainfall responses, ALB_VEG shows a smaller soil wetness response than ALB. Indeed, the difference between Figs. 5a and 5b is positive throughout the Sahel (Fig. 5c).

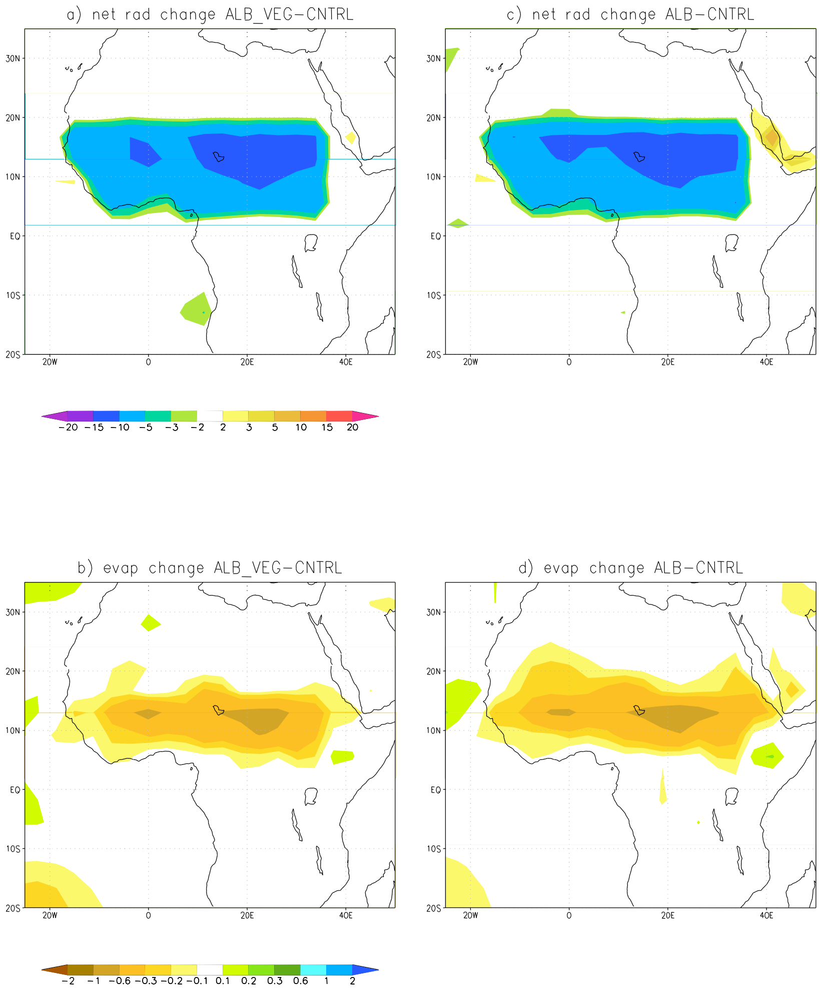

Fig. 3. a) Net surface radiation response for JJAS a) ALB_VEG-CNTRL, b) evaporation response ALB_VEG-CNTRL, c) net surface radiation response ALB-CNTRL, d) evaporation response ALB-CNTRL. Units are W/m^2 for a) and c) and mm/day for b) and d).

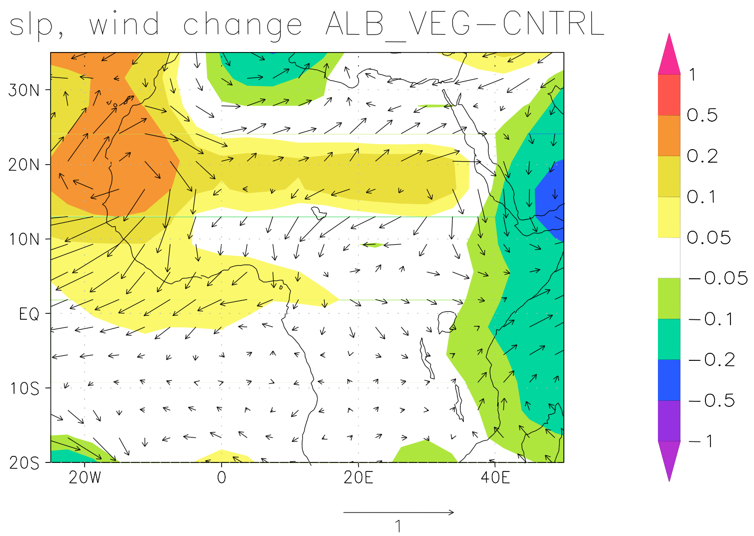

Fig. 4. Surface pressure and 925 hPa wind response for JJAS in ALB_VEG-CNTRL. Units are hPa for surface pressure and m/s for wind.

The equation for root-zone evaporation is:

$$e = b*vegc*sw \qquad (1)$$

Where vgec is the vegetation cover, sw is the soil wetness, and b depends on atmospheric conditions such as humidity, wind speed, and also on surface temperature. For simplicity we assume in equation (1) that bare soil evaporation is zero. The intepretation for the soil wetness response differences between Fig. 5a and 5b is therefore that the reduction in evaporation (surface latent heat flux) that is needed to compensate for the reduced net surface radiation is achieved in ALB_VEG by both reduced soil wetness and vegetation cover. However, since in ALB the vegetation cover is fixed to the CNTRL values, more change in soil wetness is required in order to achieve the same response in evaporation e. Of course this argument is very simplyfied as it requires that the atmospheric conditions that determine the coefficient b are similar in ALB_VEG and ALB. Given the fact that the rainfall and other dynamical response are quite similar in ALB_VEG and ALB, this assumption may be justified to a first order. If the model has dynamic vegetation (which is not the case in the simulations presented in this paper), the soil wetness is fed back to the vegetation model and a larger soil wetness will result in a larger vegetation cover, thus providing grounds for a negative feedback mechanism to the initial vegetation perturbation in ALB_VEG compared to ALB.

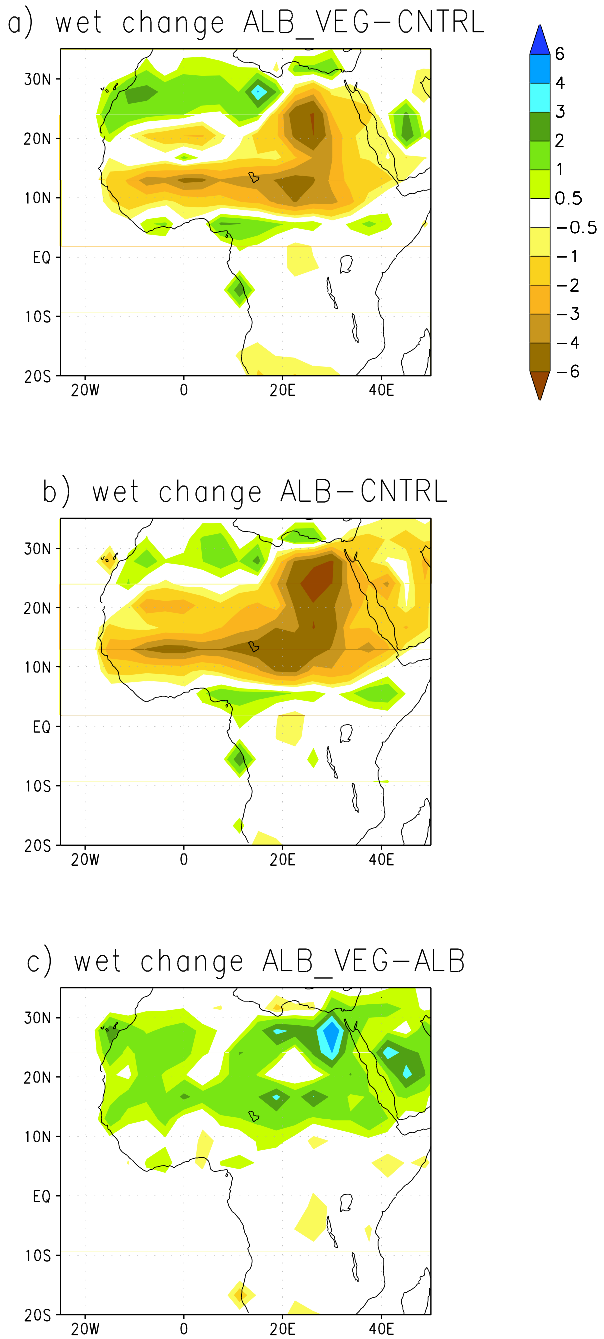

Fig. 5. Soil wetness response for JJAS in a) ALB_VEG-CNTRL, b) ALB-CNTRL, c) ALB_VEG-ALB. Units are %.

4. Summary and Conclusions

In this paper the vegetation feedback on the Sahel drought has been revisited and investigated in more details using idealized experiments with prescribed albedo and vegetation cover perturbations. The albedo effect has been confirmed as the dominant positive feedback mechanism in the vegetation feedback. As first proposed by Charney (1975), an albedo increase reduces the net surface radiation, thus leading to less favourable conditions for convective rainfall. The reduced surface net radiation is mainly compensated by a reduced latent heat flux, which corresponds to a reduced evaporation. This reduced evaporation is one important component of the total moisture budget perturbation leading to reduced rainfall. However, also the moisture divergence component is contributing and constitutes a secondary positive feedback to the vegetation impact on the Sahel drought. This is because the reduced Sahelian heating induces a high pressure slightly to the north that is weakening the Saharan heat low and leading to divergent north-easterly wind anomalies in the Sahel region. On the other hand the direct vegetation cover influence on evaporation acts as a negative feedback in the coupled atmosphere-vegetation system. This is because the latent heatflux (evaporation) reduction needed to compensate for the reduced net surface radiation is partially achieved by the vegetation reduction, therefore limiting the soil wetness reduction that could lead to a further vegetation cover decrease, and so on.

The feedbacks we have analysed here regarding the Sahel drought are purely related to vegetation/albedo variability. In a future study other potential drivers such as dust aerosol may be included the feedback chain.

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