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# Local ecosystem feedbacks and critical transitions in the climate

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## Abstract

Global and regional climate models, such as those used in IPCC assessments, are the best tools available for climate predictions. Such models typically account for large-scale land-atmosphere feedbacks. However, these models omit local vegetation-environment feedbacks that are crucial for critical transitions in ecosystems. Here, we reveal the hypothesis that, if the balance of feedbacks is positive at all scales, local vegetation-environment feedbacks may trigger a cascade of amplifying effects, propagating from local to large scale, possibly leading to critical transitions in the large-scale climate. We call for linking local ecosystem feedbacks with large-scale land-atmosphere feedbacks in global and regional climate models in order to yield climate predictions that we are more confident about.

## 1 Introduction

Continental- to regional-scale feedbacks at scales of 500–20 km between land and atmosphere have been investigated with global and regional climate models during the last two decades (Kabat et al., 2004). This research focused on regions where land-atmosphere feedbacks are strongly positive. This is because positive feedbacks could support alternative climate-vegetation regimes, for example wet and vegetated versus dry and bare (Claussen, 1997), leading to “tipping elements” (Lenton et al., 2008) in the Earth’s climate system. At the same time, results from ecological models indicated that local vegetation-environment feedbacks at scales of 100–10 m could also support alternative wet and vegetated versus dry and bare regimes at larger scales, even without accounting for large-scale land-atmosphere feedbacks (Rietkerk et al., 2004a). These local ecosystem feedbacks include important processes, such as the ability of vegetation to retain soil, containing soil water and nutrients. However, these processes are omitted in global and regional climate models. Yet, clearly, the energy balance, and hydrological and nutrient cycles connect local scales to large scales through atmospheric processes.

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In this review we address feedbacks operating at disparate spatial scales in coupled climate-ecosystem dynamics, and discuss cross-scale links between those feedbacks. We argue that the coupling of feedbacks at multiple scales in climate models, and most importantly including local ecosystem feedbacks, is an essential step to better understand and predict global climate change. We also provide a perspective on how to establish this connection.

## 2 Continental- to regional-scale feedbacks

Land surface processes, in particular those associated with vegetation cover, impact continental- to regional-scale climate (Kabat et al., 2004; Koster et al., 2004; Feddema et al., 2005; Seneviratne et al., 2006; Bonan, 2008). The mechanisms are based on water exchange and latent heat flux through the vegetation, as well as on changes in surface albedo and biogeochemical exchanges. These exchanges impact near-surface climate, precipitation formation and atmospheric circulation patterns, with possible feedbacks to vegetation cover and land surface conditions.

One of the supposed “hot spots” of land-atmosphere feedbacks is the North African desert. Surprisingly, proxy data reveal that the Sahara was covered with vegetation in the early- to mid-Holocene (10 to 6 kyr BP) (Jolly et al., 1998). This humid episode was most likely caused by changes in the precession of the Earth orbit as the northern subtropics at that time received more solar irradiation during summer than today. Presumably, stronger summer heating increased the land-ocean thermal gradient and amplified the African monsoon (Renssen et al., 2003). A strong positive feedback between vegetation cover and this monsoon rainfall has been proposed, based on the masking effect of vegetation on high surface albedo and better moisture recycling by plant transpiration (Claussen, 1997). About 6 to 4 kyr BP the climate of the Sahara shifted from a wet to a dry regime. A terrigenous dust record taken offshore West Sahara is interpreted in favour of a rapid shift from vegetated to desert conditions about 5.5 kyr BP (deMenocal et al., 2000), while proxy records from Lake Yoa located

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in the eastern part of Sahara suggest a more gradual transition (Kropelin et al., 2008). The mechanisms behind these differences are debated (Brovkin and Claussen, 2008). Nonetheless, model results suggest that this shift, regardless of its abruptness, was associated with the existence of nonlinear land-atmosphere coupling (Liu et al., 2007), 5 and alternative dry desert and moist vegetated regimes may be permitted in the region, depending on initial vegetation cover (Claussen, 1997) (Fig. 1).

Positive land-atmosphere feedbacks might also be at play in the Sahel. The Sahel climate is characterized by variability in precipitation and periodic transitions between dry and wet regimes (Nicholson, 2000). Idealized models (Entekhabi et al., 1992) suggest a bimodal distribution of soil moisture in the Sahel. Such a bimodal distribution in 10 rainfall has also been observed in the region (Nicholson, 2009). In the 1970–1980s, the region experienced intense and protracted drought. Recently, there is clear evidence of a greening trend in the Sahel (Sequist et al., 2006), and this is directly linked to increased rainfall (Nicholson, 2005). Earlier studies linked these fluctuations 15 in rainfall to changes in albedo, triggered by desertification (Charney, 1975). Climate models suggest that moisture recycling by vegetation transpiration is an important land feedback to the atmosphere (Zeng et al., 1999). More recent analyses highlighted the dependence of rainfall on changes in sea surface temperatures in the Atlantic and on changes in position and intensity of atmospheric circulation features over West Africa 20 (Nicholson and Webster, 2007; Reason and Rouault, 2006).

Extratropical regions, such as the Great Plains of North America, continental Europe and the Mediterranean region, are also proposed to be sensitive to soil moisture- and vegetation-climate feedbacks (Koster et al., 2004; Seneviratne et al., 2006). These are of potential relevance for predictions of short-term precipitation and temperature 25 variability (Koster et al., 2004), the occurrence of extreme events such as the 2003 heat wave (Fischer et al., 2007), and for large-scale circulation patterns (Fischer et al., 2007; Haarsma et al., 2009) and climate change (Seneviratne et al., 2006). A simple box model predicts that there may be significant differences between the evapotranspiration feedback of natural vegetation adjusting its cover to prevailing conditions, and

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cultivated vegetation (Baudena et al., 2008), indicating the importance of vegetation characteristics in these land-atmosphere feedbacks. Global warming could significantly impact the reported feedbacks, because warming shifts the zones with transitional climate between dry and wet conditions (e.g. the Great Plains, the Sahel region and 5 Mediterranean) (Seneviratne et al., 2006).

The Amazon is another region where positive land-atmosphere feedbacks have been reported. Rainfall recycling is very pronounced here, because most of the rainfall is transpired back to the atmosphere by the lush vegetation. Climate predictions suggest that the East Amazon forest may therefore support different regimes and shift from 10 forest to savanna (Oyama and Nobre, 2003; Salazar et al., 2007). Other proposed positive land-atmosphere feedbacks in forests encompass nutrient cycling possibly leading to similar dynamics. Emissions of volatile organic compounds from the Amazon forest into the atmosphere may prevent the loss of nutrients from the ecosystem through the deposition of reaction products (Lelieveld et al., 2008). In phosphorus-limited dry 15 forests, vegetation is sustained by atmospheric phosphorus input through rainfall, dust and fog, and canopy density positively influences dust and fog deposition (DeLonge et al., 2008). So, each of those positive land-atmosphere feedbacks might support alternating vegetation regimes between forest and savanna.

### 3 Local ecosystem feedbacks

20 Spatial self-organization of vegetation is an observed general phenomenon in ecosystems around the globe (Rietkerk and Van de Koppel, 2008). Model studies conclude that local positive ecosystem feedbacks between vegetation and environment could lead to such self-organization (Rietkerk et al., 2002; von Hardenberg et al., 2001). For instance, a small-scale feedback between vegetation cover and rainwater infiltration 25 into the soil occurs in (semi-)arid ecosystems (Rietkerk and Van de Koppel, 1997). Model studies predict that this leads to spatial self-organization of vegetation, changing the landscape, leading to optimization of water resources, and supporting

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alternative vegetated and desert regimes at larger scales, even without large-scale land-atmosphere feedbacks (Fig. 1) (Rietkerk et al., 2002; Gilad et al., 2004). Externally induced climate change could then trigger critical transitions between those regimes. Other “hot spots” of such vegetation, landscape and resource feedbacks include oligotrophic bogs (Rietkerk et al., 2004b; Eppinga et al., 2009) and savanna ecosystems (Lejeune et al., 2002). Also, literature suggests that local positive feedbacks exist between vegetation cover and nutrient retention because of the prevention of soil erosion (Rietkerk and Van de Koppel, 1997), between water and nutrient uptake by vegetation and lateral root spread (von Hardenberg et al., 2001; Lejeune et al., 2002), and between vegetation cover and reduced evaporation through shading (D’Odorico et al., 2007). Results from idealized models predict that local feedbacks could significantly affect large-scale climate and resilience of (semi-)arid ecosystems such as the Sahel (Dekker et al., 2007; Janssen et al., 2008). This is also likely to be true for other model and real coupled climate-ecosystems, because surface properties related to vegetation, landscapes and resources in ecosystems are well-known climate drivers through atmospheric processes (Nicholson, 2000).

So, vegetation has clear features of “ecosystem engineers” (Jones et al., 1994): organisms that modify their abiotic environment, feeding back to the organisms (Gilad et al., 2004; Hastings et al., 2007). Importantly, the effects of ecosystem engineers on their environment typically outlive the engineer and go beyond the spatial scale of the local feedbacks (Hastings et al., 2007). In this way, vegetation can induce landscape heterogeneity and spatial self-organization, leading to optimization of resource distribution, feeding back to the vegetation.

#### 4 Missing cross-scale links

The exploration of positive feedbacks on continental-regional and local scales, suggests that local feedbacks could lead to critical transitions between alternative regimes at larger scales. Interestingly, literature reveals that those feedbacks markedly

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influence each other and may be intimately linked (Scheffer et al., 2005; Janssen et al., 2008; Dekker et al., 2007). For example, Dekker et al. (2007) show how local vegetation-hydrology feedback could impact regional-continental evapotranspiration-precipitation feedbacks, increasing precipitation (Dekker et al., 2007). As a consequence, and strikingly, their model predicts the Sahel-Sahara boundary to be situated hundreds of kilometres more northward as compared to models not accounting for this link. The local vegetation-hydrology feedback may then affect the large-scale albedo-moisture circulation feedback, boosting hysteresis in the climate system (Janssen et al., 2008). Thus, local positive feedback could propagate to regional-continental scale through cross-scale links (Fig. 1), possibly leading to critical transitions in the large-scale climate. These are clear examples of missing cross-scale links in global and regional climate models.

Research so far leaves no doubt that the omission of cross-scale links between local ecosystem feedbacks and large-scale land-atmosphere feedbacks in global and regional climate models implies a major impediment for our ability to understand critical transitions between regimes in the large-scale climate. However, significant uncertainties remain regarding the representation of relevant processes. Also, the feedbacks and related processes inferred from models are still insufficiently validated. Moreover, positive as well as negative feedbacks may occur (Taylor and Ellis, 2006).

If the cross-scale links and critical transitions between regimes are associated with a massive loss of ecological and economic resources, this can play large havoc on human societies. Indeed, ecosystems provide important services for human survival and well-being, such as food supply, grazing land and fresh water. Vice versa, human induced cross-scale feedbacks might affect the large-scale climate. Increasing human population and land degradation have been suggested to have produced or enhanced drought conditions (“desertification”), although that idea is still controversial (Reynolds and Stafford Smith, 2002). Human induced feedbacks might have to be implemented in climate models.

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## 5 Perspectives

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The coupling of feedbacks at multiple scales is thus an essential and urgent issue to understand in order to predict ecosystem responses to climate changes and vice versa. Therefore, multi-scale models should be developed that adequately address 5 feedbacks at disparate scales. Such multi-scale approach could consist of a model hierarchy, starting with current global and regional climate models with a grid resolution of 500–20 km, including nested higher-resolution simulations (e.g. 10–1 km). The need for high-resolution global climate simulations has indeed been recognized (Heffernan, 2008), and thus the direct coupling of these scales may be feasible soon, depending 10 on computational resources. By downscaling, the employed climate models could be coupled with models representing local vegetation-environment feedbacks with a grid resolution of 100–10 m, and to represent the impact of local ecosystem feedbacks on atmospheric processes at larger scales, corresponding parameterizations could be used in upscaling (Fig. 2). Such approach could circumvent the lack of computational 15 resources, would allow taking into account the hierarchy of atmospheric processes, and would provide a feasible parameterization of the effects of local ecosystem feedbacks, and their links with large-scale land-atmosphere feedbacks. Also, it would allow determining the importance of different factors, such as vegetation and land use characteristics, for local vegetation-environment feedbacks, by studying the sensitivity 20 of climate models to different parameterizations. To constrain parameterizations in global and regional climate models, we need a better understanding of soil moisture-vegetation-climate relationships from local to large scale.

The relative importance of feedbacks and their cross-scale links should be explored 25 in advance with idealized models that contain few state variables and parameters. This is because these models can reveal a significant range of complex behaviour observed in real systems, despite their simplicity (Zeng et al., 2006; D'Odorico et al., 2007). Such simplified models are useful to explain phenomena observed both in nature and in complex global and regional climate models. Idealized models could be validated

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using newly available observations; e.g. new satellite measurements and ground measurement networks (Nemani et al., 2003). While simple models are needed for understanding the relative importance of feedbacks and their cross-scale links, complex global and regional models are better suited for climate predictions, and to investigate the involved feedbacks in their full complexity. We strongly advocate the integrated use of simplified, intermediate and full complexity models, ranging from local to large scales. By following this approach we will achieve further understanding and we envisage climate predictions that we are more confident about.

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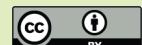
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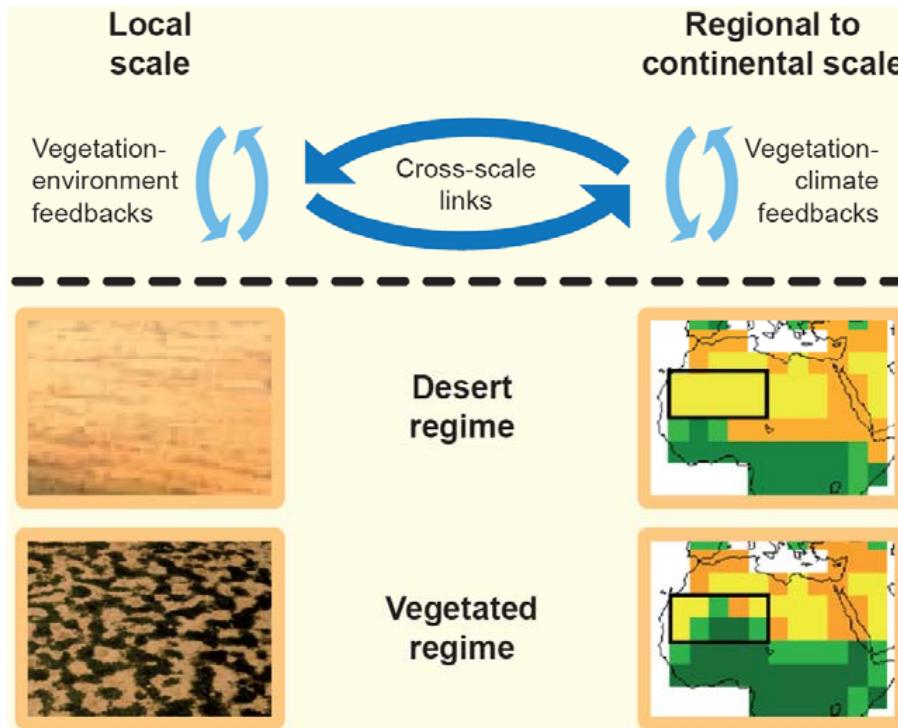
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**Fig. 1.** Feedbacks, associated scales (local, regional-continental) and alternative regimes (dry desert, wet vegetated). Wet vegetated and dry desert regimes at local scale represent self-organized vegetation (green) and bare soil (brown-yellow) (Rietkerk et al., 2002). Two climate regimes at regional-continental scale represent wet vegetated (green) and dry desert (yellow) (Claussen, 1997) areas in Africa. The dark blue arrows are the cross-scale links between feedbacks operating at disparate scales that are missing in global and regional climate models.

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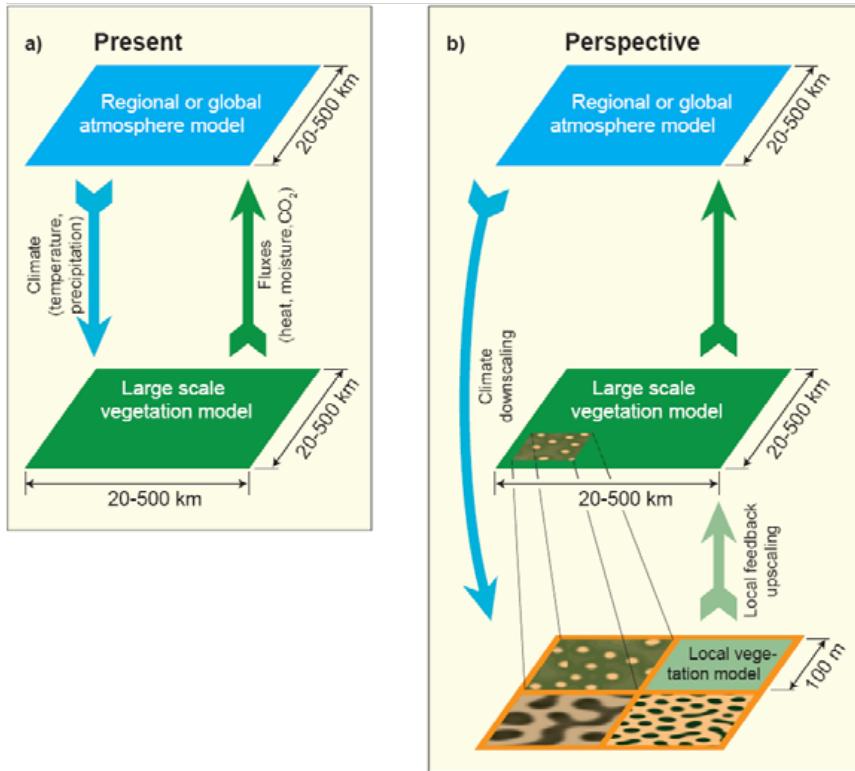
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**Fig. 2.** Linking of regional- to continental-scale land-atmosphere feedbacks with local vegetation-environment feedbacks by using a model hierarchy. **(A)** Current climate models account for large-scale land-atmosphere feedbacks, but do not account for local ecosystem feedbacks. **(B)** Linking large-scale land-atmosphere feedbacks with local vegetation-environment feedbacks by downscaling the climate model to the local feedback model. Upscaling is based on model outcomes of the local feedback model, through parameterization of the large-scale vegetation model, leading to improved fluxes to the atmosphere model.