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Viewpoint

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 may be crucial for critical transitions in ecosystems at larger scales. In this viewpoint paper, we propose 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 improve climate predictions.

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', and associated 'critical transitions', in the Earth's climate system (Dakos et al., 2008; Lenton et al., 2008). 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, and critical transitions between those regimes, 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 water and nutrients.

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However, these processes are omitted in global and regional climate models. Yet, the energy balance, and hydrological and nutrient cycles connect local scales to large scales through atmospheric processes. For example, plants clumping into self-organized patterns allow a more efficient use of water and nutrients in comparison with homogeneous plant cover, affecting heat and moisture fluxes on local to large scales (Dekker et al., 2007; Janssen et al., 2008; Scheffer et al., 2005). Also, increased canopy density in forests may prevent the loss of nutrients through increased large-scale deposition of dust, fog and reaction products of emitted volatile organic compounds from leaves (DeLonge et al., 2008; Lelieveld et al., 2008).

In this viewpoint we build up an argument for addressing feedbacks operating at disparate spatial scales, including local ecosystem feedbacks, in global and regional climate models. We discuss cross-scale links between those feedbacks, focussing on regions where these are supposed to be important. We argue that the coupling of feedbacks at multiple scales in climate models, including local ecosystem feedbacks, is an essential step to better understand and predict climate change and carbon balances, especially on regional scale. We also provide a perspective on how to establish this connection.

2. Local ecosystem feedbacks

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 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 alternative vegetated and desert regimes at larger scales, even without large-scale land-atmosphere feedbacks (Fig. 1) (Gilad et al., 2004; Rietkerk et al., 2002). 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 (Eppinga et al., 2009; Rietkerk et al., 2004b) 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 (Lejeune et al., 2002; von Hardenberg et al., 2001), 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 seems to belong to the class 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 individual organism 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.

3. Continental- to regional-scale feedbacks

Land surface processes, in particular those associated with vegetation cover, impact continental- to regional-scale climate (Bonan, 2008; Dekker et al., 2010; Feddema et al., 2005; Kabat et al., 2004; Koster et al., 2004; Seneviratne et al., 2006). The mechanisms are based on water exchange and latent heat flux through the vegetation, as well as on changes in surface albedo,

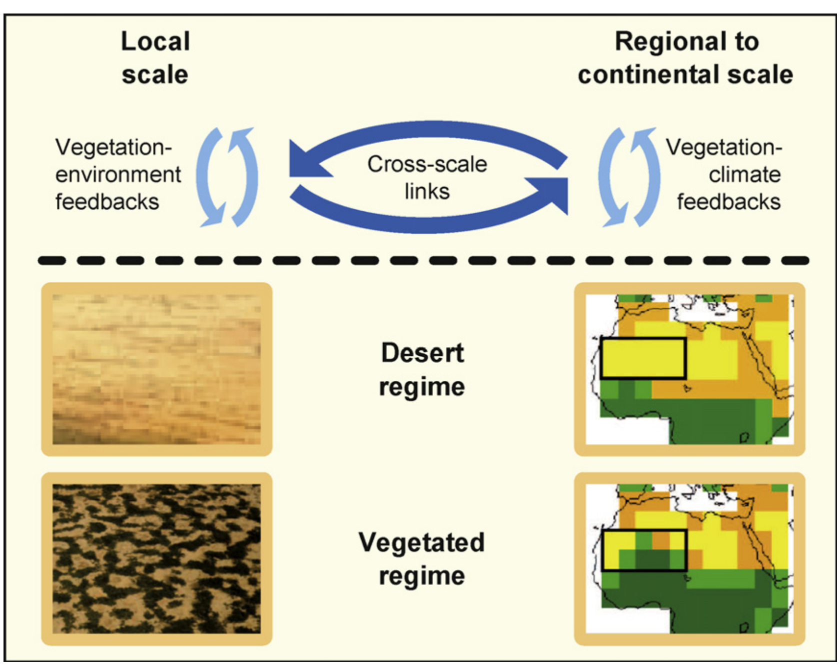

Fig. 1. Feedbacks, associated scales (local, regional-continental) and alternative regimes (dry desert, wet vegetated). Wet vegetated and dry desert regimes at local scale represent self-organized vegetation (green) and bare soil (brown-yellow) (Rietkerk et al., 2002). Two climate regimes at regional-continental 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.