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Simulation of vegetation feedbacks on local and regional scale precipitation in West Africa

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ABSTRACT

Planned changes to land use in West Africa have been proposed to both combat desertification and to preserve biodiversity in the region, however, there is an urgent need for tools to assess the effects of these proposed changes on local and regional scale precipitation. We use a high-resolution, convection-permitting numerical weather prediction (NWP) model to study how the initiation and propagation of mesoscale convective systems (MCS) depends on the surface vegetation cover. The simulations covered a 4-day period during the West African monsoon in August 2006. In many aspects of the simulations, there was evidence of vegetation type exerting a significant influence on the location of precipitation where the influence of orography and coastal water was minimal. In this study, vegetation was classified according to the fractional coverage of tree (>30%) and grass (>30%) plant functional types. Tree-grass boundary cover was defined where more than 3 grid cells of both tree and grass occurred in a moving 3 × 3 window, which was further enlarged using a 3 grid cell (∼12 km) buffer. We found that over the whole study region (5N to 17N and 11W to 9E) 33.8% of convective initiations occur over tree-grass boundaries that cover only 28.4% of the land surface. This is significantly more than would be expected by chance ($p = 0.0483$), providing support to the hypothesis that vegetation gradients provide heat and moisture gradients, of a similar magnitude to that of soil moisture. Additionally, we found that on average, more time under an MCS occurred over boundary cover and orography, followed by tree cover, during the afternoon and evening period, thus supporting the hypothesis that land cover type influences the location of larger propagating systems. Contrasting patterns were found in the quantity of precipitation between small-scale convective cells and larger scale MCS. More small-scale precipitation accumulated, on average, over grass cover during the afternoon period, indicating a tendency for small-scale convection, initiated over boundaries, to prefer the drier and warmer grass side of vegetation boundaries in the afternoon period. However, once these smaller scale convective cells merge together to form larger MCS, a tendency for the most intense precipitation to fall over tree cover was observed. When intense precipitation (>10 mm per hour) occurred simultaneously over tree, boundary and grass cover, we found the highest precipitation rate to be most frequently over tree cover (48.4%), and least frequently over boundary cover (19.9%), indicating a preference of MCS for cooler, more moist forest cover. These results show for the first time that convection-permitting NWP models do exhibit responses to vegetation similar to those observed in the real world, and therefore are useful tools to assess the impacts of proposed future land use changes.

1. Introduction

Human induced land use change has been well documented to have feedbacks to the climate system in simulations of global and continental scale climate change (Mahmood et al., 2014). Increasing observational evidence points towards vegetation in the tropics having an influence over the atmospheric boundary layer at length scales of up to 10 km (Garcia-Carreras et al., 2010; Knox et al., 2011). Such spatial scales are beyond the scope of most climate models, but the potential for vegetation to exert further influence on local and regional precipitation patterns via high-resolution feedback processes has yet to be fully explored.

Land use change is occurring rapidly in many parts of West Africa, including deforestation, as well as planned and unplanned

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afforestation (Hansen et al., 2013) with little understanding as to the effects that changes in forest cover may have on monsoon rainfall. For example, plans to construct a Great Green Wall across the Sahel to combat desertification may have unintended consequences for local precipitation patterns. If we are to offer advice to land use planners in the region on the consequences of large-scale changes to the vegetation, we need models that are capable of capturing the observed interactions between the land surface and the boundary layer. There are large uncertainties in the effects of land use change on tropical precipitation, possibly related to issues of the scale of processes involved, but also very strongly related to the representation of convection. (Taylor et al., 2013) show that convective representation is a much stronger control on the statistical relationship of rainfall with the land surface, than model resolution. Indeed, the response of rainfall to the land-surface state seems to have the wrong sign in GCMs (Taylor et al., 2012), and this incorrect response has been shown to be due to the failure of parameterised convection schemes to faithfully locate convection according to surface and low-level conditions (Taylor et al., 2013).

Observational studies have shown that strong gradients of heat and moisture can occur on vegetation boundaries such as those between cropland and forest (Shaw and Doran, 2001; Garcia-Carreras et al., 2010). Low-level horizontal pressure gradients are created by generally greater transpiration and soil evaporation associated with forest cover compared to cropland, and higher albedo and land surface temperatures associated with croplands compared to forest cover. These low-level thermal gradients can induce 'vegetation breezes' as simulated by (Letzel and Raasch, 2003; Kang and Bryan, 2011) which in turn can control the occurrence of convection in two ways (Garcia-Carreras et al., 2011). Firstly, the convergence provided by the vegetation breeze leads to upward motion that, through nonlinear dynamics of the flow, is strong enough to overcome convective inhibition (CIN) and initiate convection (Segal and Arritt, 1992). Secondly, the convergence also concentrates low level humidity, reducing dry entrainment from above, and therefore maximises the equivalent potential temperature (θe) in the convergence zone close to the vegetation boundary (Garcia-Carreras et al., 2011). This θe maximum provides high convective available potential energy (CAPE) and low CIN, for the initiation of local scale convection. In idealised modelling studies, it was also found that the breeze circulations lead to subsidence on the cool side of the vegetation boundary, causing a significant (half) reduction in the rainfall over the remaining forest (Garcia-Carreras and Parker, 2011).

If convective storms achieve significant size and longevity, they are termed *meso*-scale convective systems (MCS). MCS can contribute between 80 and 90% of annual precipitation to parts of the Sahel (Mathon and Laurent, 2001). However, in more southerly parts of West Africa, MCS may deliver 50% or less of the rainfall, with the other rain dominated by shorter-lived, isolated convective rain (Fink et al., 2006; Jackson et al., 2009). An MCS is defined as a cloud system that produces a contiguous precipitation area on the order of 100 km or more in horizontal scale in at least one direction (American Meteorological Society, 2015). MCSs grow and propagate through the action of mesoscale flows, particularly the cold pool, causing triggering of new convective cells all the time, therefore they are less sensitive to the patterns of local-scale convergence in their environment, and are more sensitive to the available moisture and CAPE (Corfidi, 2003). Surface observations in the vicinity of Niamey (Taylor and Lebel, 1998) as well as idealized modeling of MCSs have shown how a pre-existing MCS will deliver more rainfall over a boundary layer with a higher specific humidity than its drier surrounding environment.

This therefore indicates two competing responses. Convective initiation is on the warm, dry side of boundaries and therefore local convection and the initial stages of MCS rain occur mostly in those areas, but mature MCS are thought to rain more over humid surfaces. This would indicate an additional feedback of the land surface state on the direction an MCS travels (Wolters et al., 2010). If this is robust, then the net effect of the land surface on precipitation totals will depend on whether the climatology of a given zone is influenced by locally generated precipitation (small scale processes) or organized MCS precipitation (large scale processes).

Recent studies (Taylor et al., 2013; Birch et al., 2014) demonstrate that convection-permitting models provide a step change in the response of convection to the land surface which closely matches observations, even at relatively low spatial resolutions (12 km). Convection-permitting models run over large domains therefore provide a valuable tool to evaluate the net effect of competing mechanisms that control the rainfall response to the surface. In this paper, we will examine the spatial coincidence of precipitation in relation to land cover from a high-resolution limited area simulation covering the entire West African monsoon region (approximately 3700 km × 2400 km), run with explicitly resolved convection. The combination of a high spatial resolution and a regional-scale domain allows us to explore, for the first time, mechanisms occurring across a range of scales in an integrated manner, in order to answer the following questions:

1. Location of rainfall

a.) Does convection initiate preferentially in the vicinity of forest-grass boundaries?
b.) Do MCS have a preference for moving over a certain land cover type?

2. Quantity of precipitation

a.) Is there more localised precipitation over boundaries?
b.) Does a mature MCS deliver more rain to different vegetation types within its swath?

2. Methodology

2.1. Numerical weather prediction model

The Met Office Unified Model [MetUM; Davies et al., 2005] was used to create a dynamically downscaled 4 km resolution simulation similar to those described in (Holloway et al., 2012). The model is therefore configured in a similar way to that used for short-range weather prediction for the UK with, most notably, convection being represented explicitly. Furthermore, following (Holloway et al., 2012), a 3-dimensional Smagorinsky-like (Smagorinsky, 1963) sub-grid turbulence scheme is employed, which replaces the 1-dimensional planetary boundary layer (PBL) parametrization scheme that would be used in coarser resolution simulations. This 3D sub-grid turbulence scheme governs the horizontal and vertical fluid flow via equations that account for sub-grid eddy viscosity and diffusivity. The classical Smagorinsky approach is extended by reducing the mixing length close to the surface in order to account for effects of the roughness of the land surface (a more detailed description of which can be found in (Halliwell, 2007; Pearson et al., 2014). The surface roughness length for momentum is calculated in the Joint UK Land Environment Simulator (JULES) land surface model as a multiple of PFT-dependent vegetation height (~28 m for broadleaf tree and ~1.25 m for C4 grass cover over the whole domain) and a PFT-specific 'rate of change' constant (0.05 for broadleaf tree, and 0.1 for C4 grass) that varies depending on plant functional type (PFT) (Best et al., 2011). Therefore the roughness lengths of broadleaf tree cover and C4 grass are 1.4 m and 0.125 m respectively. JULES also calculates heat and moisture fluxes to the PBL, thereby establishing a mechanistic link between the land sur-