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Interactions between vegetation, atmospheric turbulence and clouds under a wide range of background wind conditions

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ABSTRACT

The effects of plant responses to cumulus (Cu) cloud shading are studied from free convective to shear-driven boundary-layer conditions. By using a large-eddy simulation (LES) coupled to a plant physiology embedded land-surface submodel, we study the vegetation–cloud feedbacks for a wide range (44) of atmospheric and plant stomatal conditions. The stomatal relaxation time is prescribed as an instantaneous, symmetrical (10, 15 and 20 min) and asymmetrical (5 min closing, 10 min opening) response, and the background wind ranges from 0 to 20 m s^{-1}. We show that in free convective, non-shading (i.e. transparent) cloud conditions the near-surface updraft region is marked by an enhanced CO_2 assimilation rate (A_n; 7%) and increased latent (LE; 9%) and sensible heat (H; 19%) fluxes. When we introduce Cu shading, we find an enhancement in plant transpiration and CO_2 assimilation rates under optically thin clouds due to an increase in diffuse radiation. However, these effects vanish when a background wind is present and the Cu are advected. Optically thick clouds reduce the assimilation rate and surface fluxes under all simulated wind conditions.

With increasing background wind, the shaded surface area is enlarged due to Cu tilting. The consequent decrease in surface fluxes by a reduction in incoming radiation, is partly offset due to an enhancement in the surface exchange and turbulent mixing as a result of stronger wind speeds. Different and non-linear processes control the H and LE response to shading. H is mainly radiation driven, whereas plant responses dampen the shading effects on LE. As a result, the regional averaged (48 km^2) reduction in H and LE are found to be 18% and 5%, respectively, compared to non-shading cloud conditions. Surprisingly, a nearly uniform regional net radiation reduction of 11% is found, with only a deviation between all 35 Cu shading cases of 0.5% (i.e. 1.2 W m^{-2}) at the moment of maximum cloud cover. By comparing four representative simulations that are equal in net available energy, but differ in interactive and prescribed surface energy fluxes, we find a relative reduction in cloud cover between 5 and 10% during the maximum cloud cover period when the dynamic surface heterogeneity is neglected. We conclude that the local and spatial dynamic surface heterogeneity influences Cu development, while the Cu–vegetation coupling becomes progressively weaker with increasing stomatal relaxation time and background wind.

1. Introduction

As long as more than a century ago, an anonymous writer raised a question in the literature regarding whether the vegetation could influence cloud development, and consequently the occurrence of rainfall (Mon, 1907). While the answer provided to that question is debatable, our understanding on the vegetation–cloud interaction is still very limited. During the 1990s, progress was made on a more profound understanding of the interactive vegetation–cloud system using large scale observations (e.g. Carleton et al., 1994) and modeling (e.g. Chen and Avissar, 1994; Hong et al., 1995; Wetzel et al., 1996). In those studies, the land surface was prescribed, thereby not permitting interactive surface responses to atmospheric perturbations. To understand the effect of smaller-scale processes, Monteith (1995) suggested linking plant stomatal responses to a clear sky convective boundary layer (CBL) development, and vice versa. However, he concluded that "*a combined complex plant and atmosphere model would be an unmanageable monster from which useful output would be extremely hard to obtain*", which

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illustrates our current limited understanding of the vegetation–cloud system.

Advances in computational power and improved understanding of fundamental modelling concepts (e.g. sub-grid representation) gave rise to systematic studies on forcings in the vegetation–cloud system. Investigators utilised the Large-Eddy Simulation (LES) technique to study interactions between vegetation and turbulent transport by varying the leaf-area index (e.g. Albertson et al., 2001), the sensitivity of cumulus (Cu) development to soil moisture content (e.g. Golaz et al., 2001), or the effect of a local decrease in surface fluxes due to Cu shading on the CBL structure (Schumann et al., 2002). In the latter study, they focused on an initially homogeneous surface and modelled the surface effects to local shading as instantaneous. For hovering Cu, they found that the convective turbulent motions were significantly influenced when Cu shading was taken into account, while the solar inclination angle had no significant effects on atmospheric structure. A subsequent step, was to couple an LES to an interactive land-surface submodel (LSM) and investigate the influence of aerosol properties on Cu clouds (Jiang and Feingold, 2006). They showed that the LSM responded to changes in cloud optical properties and spatially affected the surface energy balance (SEB), leading to a reduction in the strength of convection, cloud fraction and depth. In 2014, both Lohou and Patton (2014) and Vilà-Guerau de Arellano et al. (2014) published their findings of localized Cu shading on an interactive vegetated surface and found large effects on cloud and surface properties. More specifically, Lohou and Patton (2014) showed that Cu shading leads to a non-linear SEB response, enhancing the evaporative fraction (EF) by 2–3%, with the reduction in shaded areas having a greater effect on the sensible heat flux (*H*; 7–15%), and less on the latent heat flux (LE; 5%). While the surface response was immediate in the case of Lohou and Patton (2014) and earlier studies, Vilà-Guerau de Arellano et al. (2014) introduced a symmetrical plant stomatal relaxation time (of ∼15 min), based on observations from Vico et al. (2011). In their free convection case (i.e. no background wind), they showed that Cu are significantly affected by vegetation. Cu shading induced both spatial and temporal heterogeneity in the SEB, which affected the cloud liquid water path. Furthermore, they concluded that the plant response has consequences for local turbulence, and thus could affect cloud properties on short time-scales. To further quantify these results, Horn et al. (2015) investigated the effects of spatial variability in surface fluxes due to Cu shading on characteristic boundary-layer length scales for a tropical free-convection case (Ouwersloot et al., 2013). They reported that cloud shading reduces turbulent kinetic energy (TKE) production in the subcloud layer, resulting in a decrease in thermal lifetime and interthermal distance. They also concluded from their LES experiments that the cloud population was affected by Cu shading, which produced smaller and more clouds, while the cloud cover remained similar compared to radiatively transparent clouds. In order to investigate the effects of cloud shading location on secondary circulations, Gronemeier et al. (2016) modelled in a free convective situation four solar inclination angles, which affected their prescribed sensible heat flux. They show that a small solar angle negatively influences Cu development, while a larger angle increases the occurrence and depth of Cu, which suggests a decoupling between the vegetation and clouds. However, no adaptations of plant response or distinctions between direct or diffuse radiation were taken into account, which makes it difficult to extrapolate their results for an interactive vegetated surface. Related to this, observations by Freedman et al. (2001) and Min (2005) showed that the partitioning into diffuse and direct radiation by Cu is essential to capture vegetation responses to Cu shading, which enhances both the light-use and water-use efficiency (WUE) of the vegetation (Freedman et al., 2001).

Near-surface environmental conditions are essential in the vegetation–Cu system, as local fluctuations in the atmospheric state (e.g. temperature, moisture, wind) introduce spatial and temporal heterogeneity in the vegetation state (e.g. see Fig. 1 in Betts et al., 1996). As a result, vegetation patterns interact with atmospheric structures, and vice versa (e.g. visible in Fig. 1b–d in Vilà-Guerau de Arellano et al., 2014). Focusing on the near-surface horizontal wind speed (*U*), which plays a major role in vegetation–atmosphere exchange, Moeng and Sullivan (1994) found streaky patterns in *U* that suggest line-wise patterns in the state of the vegetation (e.g. enhanced transpiration rates) as well. As these atmospheric structures can range from cellular convection under free convective conditions to roll vortices in wind-shear conditions, it is to be expected that *U* affects the vegetation–Cu interaction in several ways. Since the atmospheric structure not only affects the vegetation, but also Cu development and tilting, it affects the partitioning between direct and diffuse radiation reaching the surface, thereby complicating the interactions even further.

In order to understand the relationships between horizontal wind perturbations, plant adaptation time, atmospheric structure and Cu shading and development, we designed numerical experiments to systematically break down the complexity of the interactive vegetation–Cu system by performing a sensitivity analysis for five plant stomatal response times in combination with seven wind-speed cases, ranging from cellular to roll-vortex convection. To better understand the effects of Cu shading, we also included a radiatively transparent Cu case. To the best of our knowledge, no research on the combination of plant relaxation time, cloud shading and wind conditions has been carried out on this detail. We therefore systematically increased the complexity throughout the paper. After describing the numerical modelling and cases, which are introduced in Section 2, we started by investigating the effects of horizontal wind perturbations on the vegetation (Section 3). Next, we added the presence of Cu shading in Section 4 and explored the effect of cloud movement on the vegetation. In Section 5, we combined the knowledge gained thereby explain the effects of Cu shading on the vegetation, and its feedback to Cu development for all wind and plant adaptation cases. Finally, our results are put into perspective in a discussion (Section 6), which is followed by the conclusions in Section 7.

2. Numerical simulations

The numerical experiments describe a typical early autumn day in the Netherlands and are validated against a complete set of observations (Vilà-Guerau de Arellano et al., 2012), where dynamically forced Cu arise over an interactive grassland (Casso-Torralba et al., 2008). To represent the formation of roll vortices properly, the simulated area covers 48 km × 48 km and is for 90% covered by C3 grass. The three-dimensional atmospheric fields were solved up to a height of 5.5 km, with horizontal and vertical resolutions of 50 m and 12 m, respectively. Time integration was performed by a third-order Runge–Kutta scheme. An adaptive time-step approach was taken, limited to a maximum of 20 s, after which a 1-min average was calculated. To numerically integrate the flow equations, we utilised the Dutch Atmospheric Large-Eddy Simulation (DALES; version 4.1) the core details of which are described in Heus et al. (2010) and recent extensions in Ouwersloot et al. (2016). At the top one-third of the domain, a sponge layer is applied that prevents the reflection of gravity waves (Heus et al., 2010). Surface characteristics were calculated by an interactive plant physiological sub-model, A-gs (Jacobs and De Bruin, 1997; Ronda et al., 2001), which enabled us to investigate localised cloud-shading effects on surface characteristics. The coupling of the surface boundary to the atmosphere is performed by applying the transfer laws of Louis (1979). For details, see Heus et al. (2010). All the experiments considered a situation in which the sun is directly above the cloud, although the amount of radiation depends on the solar angle (Pedruzo-Bagazgoitia et al., 2017). This idealises the interactions, as the maximum decrease in radiation occurs directly below the cloud, thereby reducing the turbulent intensity in its updraft (Schumann et al., 2002; Gronemeier et al., 2016). Using the Delta-Eddington approach (Joseph et al., 1976),