DIFFUSE RADIATION IN
BOUNDARY-LAYER
CLOUD-VEGETATION FEEDBACKS

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M.Sc Thesis
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Abstract

We studied the impact of diffuse shortwave radiation on the cloud-surface feedbacks, and how these affect the development of an aerosol-free convective boundary layer at mid-latitudes on a typical summer day. We developed and partially validated a new two-leaf radiative transfer scheme with sunlit and shaded leaves inside the canopy discriminating direct and diffuse radiation, and compared it to the a one-leaf canopy scheme. Additional sensitivity tests for light composition (direct/diffuse) and canopy Leaf Area Index (LAI) were carried out. By using the delta-Eddington approximation for the interaction between shortwave radiation and shallow cumulus clouds, and the two different in-canopy radiative transfer schemes, we designed 6 numerical experiments on LES. All the experiments share the same soil, vegetation and atmospheric conditions, and consist of: an explicit calculation of diffuse light both in clouds and in the canopy; an identical case where diffuse light from clouds is neglected; and a third case with explicit calculation of diffuse light in clouds and a one-leaf $A_{gs}$ canopy scheme insensible to the direct or diffuse character of light. All three experiments are repeated for LAI=2 and LAI=5. With these experiments we were able to understand the effects of diffuse radiation created by shallow cumulus clouds on the atmospheric boundary layer (ABL). More specifically, we observed the diffuse light induced changes on surface fluxes, boundary layer buoyancy and vertical profiles, and on the characteristics of the shallow cumulus clouds created during the day.

Results suggest that diffuse radiation from clouds, accounting for a small part of the total radiation reaching the surface (7%), affects surface energy balance due to increased plant photosynthesis. Furthermore, it increases the buoyancy of the boundary layer without varying the vertical profiles significantly. However, the impact on clouds shows clear links to diffuse radiation, with rises of cloud cover and liquid water path of around 25%. The comparison of the developed two-leaf radiative transfer scheme with the existing one-leaf $A_{gs}$ shows that the one-leaf scheme was managing light as almost pure diffuse, meaning a higher absorption efficiency by plants. This higher absorption rates lead to a less buoyant, colder and more moist boundary layer, with no significant effects on clouds characteristics. An increase on LAI is not found to affect significantly the evolution and characteristics of the boundary layer.
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Chapter 1

Introduction

The atmospheric boundary layer (ABL), defined as that part of the troposphere that is directly influenced by the presence of the earth’s surface, and responds to surface forcings with a timescale of about an hour or less (Stull, 1988), has been subject of study for decades. Many of the meteorological phenomena affecting our every day life are actually coming from, or are influenced by, the state of the boundary layer. Air quality conditions or power generation by wind energy, for example, are significantly dependent on the mechanisms driving the boundary layer.

By definition, the ABL is strongly influenced by the surface. The scientific community has long studied the impacts of surface roughness and fluxes on the ABL (Rao et al., 1974; Troen and Mahrt, 1986; Stull, 1988). As science developed, the coupling between boundary layer and surface attracted more attention, including the underlying feedbacks (Jacobs and De Bruin, 1997). This research showed that the surface of the earth and its boundary layer above are clearly coupled and influence each other. Actually, these couplings are important not only at small time scales, but also at timescales in the order of months (Boussetta et al., 2013). Under certain conditions boundary-layer clouds are created within this few-kilometer thick layer. If the photosynthetic processes of vegetation are considered, the presence of clouds is specially important, and leads to changes in the whole boundary layer (Freedman et al., 2001). Focusing on vegetation sensitivity to climate change and an atmosphere with increasing CO₂ concentration, Vilà-Guerau De Arellano et al. (2012) showed plants to suppress the creation of boundary-layer clouds under warming and rising CO₂. By explicitly simulating the creation of clouds, García-Carreras et al. (2011) focused on how the mesoscale flows created by surface heterogeneities impact the convection initiation. The creation of boundary layer clouds has at the same time a large impact on the evolution of the boundary layer, due to both their radiative and dynamical effects (Cotton et al., 1995; Neggers et al., 2006; Van Stratum et al., 2014).

Many of the interactions between clouds and vegetation take place at the small spatial and temporal scales, in the order of meters and minutes, or even seconds. Thus, in order to simulate properly these processes models with high enough resolution are needed. LES models are the best option for these cases, since they are able to simulate processes at the needed scales, while resolving most of the turbulent motions in the ABL. We will use the Dutch Atmospheric Large Eddy Simulation (DALES) (Heus et al., 2010), as explained in Section 2.1. LES models have been used in the last decades to obtain more realistically simulated boundary layers, allowing a better understanding of the underlying processes and feedbacks. By using a LES model, Avissar and Schmidt (1998) investigated the sensitivity of the convective boundary layer to spatial variations of sensible heat (SH). Focusing on the clouds, Horn et al. (Submitted) explored the characteristic ABL length scales due to shadowing. Golaz et al. (2001) showed that cloud fraction was nearly
insensitive to soil-moisture driven changes in surface flux partition under prescribed surface fluxes. However, they found significant dependencies of cloud base height and turbulence on the latent and sensible heat flux ratio. Van Stratum et al. (2014) showed, by using a LES and observation-based prescribed surface fluxes, that clouds impact on the structure of ABL due to different mass fluxes compared to clear sky situations. By adding a land surface model coupled with LES, Lohou and Patton (2014) found that the shading of clouds has a different impact on sensible and latent heat fluxes at the surface. Also coupling a land surface model to a LES, Huang and Margulis (2011) investigated the effect that atmospheric stability has under different soil moisture conditions on cloud characteristics. With a similar coupling between LES and a land surface model, Chlond et al. (2014) simulated the effects of soil moisture and atmospheric conditions, concluding that the convection of shallow cumulus strongly depends on the stability and water content of the boundary layer, as well as the soil moisture. However, all the previous results are limited by the fact that the vegetation in the land surface model was not sensitive to radiation or CO$_2$ concentrations, limiting the creation of surface heterogeneities associated to clouds. Vilà-Guerau de Arellano et al. (2014) was able to show, by making use of the photosynthesis model by Ronda et al. (2001) in a land surface model coupled to LES, that the creation of shallow cumulus clouds in the boundary layer is affected by the photosynthetic efficiency of plants. Similarly, Sikma (2014) worked on the influence on the feedback between vegetation and clouds when stomatal response to radiation is delayed or when wind is present, as well as how these factors affect the likelihood of deep convection to occur in the late afternoon.

Despite the large amount of research carried out on cloud and vegetated surface feedbacks using LES experiments, the shading of clouds has been usually limited to a decrease in radiation at the surface, without discriminating between diffuse and direct radiation. Diffuse radiation is created when the direct beam from the sun is reflected by a particle in the atmosphere. Most commonly, aerosols and cloud water droplets are the reason for the diffuse radiation reaching the surface. Diffuse radiation is an important part of the radiation reaching the earth surface. What is more, around 40% of the Photosynthetic Active Radiation reaching the surface is diffuse (Mercado et al., 2009) and the expected increase of water vapor in the atmosphere is very likely to increase this percentage in the coming decades (Pounds and Puschendorf, 2004). In our case, we will focus on the diffuse radiation coming from the shallow cumulus formed in the boundary layer. Additionally, diffuse radiation is thought to be more efficiently absorbed by vegetation, leading to higher values for carbon uptake both observed (Oliphant et al., 2011; Niyogi et al., 2004; Gu et al., 2003) and measured (Alton et al., 2007; Min, 2005; Roderick et al., 2001). Radiative transfer models usually account for the diffuse radiation created inside the canopy, due to reflection and scattering effects. However, to our knowledge there has been no systematic research coupling diffuse radiation sensitive canopies and the diffuse radiation created by clouds. Thanks to the high spatiotemporal resolution of the DALES, we will be able to explicitly simulate the processes in which diffuse radiation is of importance, and to investigate the immediate effect of diffuse radiation in the ABL. Therefore, this study in DALES intends to give a general characterization of the consequences of light modification by clouds in the vegetation, deepening into the effects this interaction has in the ABL.

In order to study the effect of diffuse radiation in the boundary layer system, the following research questions are proposed:

- How does the dynamic partitioning of direct and diffuse radiation generated by clouds influence the energy and CO$_2$ fluxes at the surface?
- Are the ABL dynamic processes affected by the diffuse radiation from the clouds?
- Do the changes in vegetation performance due to diffuse radiation from clouds affect the boundary-layer cloud dynamics?

- Does a two-leaf A-gs canopy radiative transfer scheme imply significant differences in the boundary layer and boundary-layer clouds compared to a one-leaf A-gs scheme?

- Are the feedbacks concerning diffuse radiation from clouds significantly sensitive to the canopy Leaf Area Index? Are the differences between experiments increased when LAI grows?
Chapter 2

Methods

2.1 Model description

In order to understand the links underlying between diffuse radiation, surface, boundary layer and boundary-layer clouds, we use a state of the art LES model: DALES. The Large Eddy Simulations stand as very powerful tools to investigate the physics and phenomena in the atmospheric boundary layer. Version 4.0 of DALES has been used. The high spatial resolution of this model, in the order of meters, allows DALES to resolve explicitly around 90% of the turbulent motions taking place in the boundary layer. This implies a much smaller dependence of the results on the parametrizations. We make use of an all-or-nothing microphysics scheme, assuming condensation if the air is saturated within each gridbox, and no liquid water present otherwise. Periodic boundary conditions are set on the grid sides, creating an infinite domain. Furthermore, some additions have been done in the model in order to discriminate between direct and diffuse radiation. The delta-Eddington method (Joseph et al., 1976; Barbaro, 2015) is used to account for the direct radiation reduction and conversion to diffuse radiation when it interacts with droplets inside the cloud. A brief description of this method is given in Section 3.1. Additionally, a new radiative transfer model inside the canopy is used in some of the experiments. This model, inspired by Jacobs and De Bruin (1997) considers sunlit and shaded leaves, direct and diffuse radiation coming from above and additional diffuse radiation created due to scattering by leaves and reflection by the ground. The model is described in detail in Section 3.2.

2.2 Numerical experiments and research strategy

To answer the questions proposed at Section 1, 3 simulations have been selected and repeated for different LAI values. All experiments start at 7:00 UTC (9:00 LT) and run for 10 hours, simulating an ideal summer day with no wind and developing a convective boundary layer. They all run under a resolution of 50 x 50 m in the horizontal and 12 m in the vertical. The DIF experiments are the reference experiments and analyze diffuse radiation explicitly with new
Figure 2.1: Representation of the 6 experiments analyzed. Yellow and red arrows represent direct and diffuse radiation, respectively. The two leaves represent the two-leaf canopy model with sunlit and shaded leaves. The only difference between experiments and its analogues with a 5 at the end is the switch from LAI=2 to LAI=5.

additions to the model. The delta-Eddington model, explained in Section 3.1, is used for radiative transfer through the clouds. The radiative scheme developed during this thesis and explained in Section 3.2 is used for radiative transfer, stomatal conductance and net photosynthesis rate calculations inside the canopy. NODIF experiments use same settings as DIF experiments, with an additional feature: after been calculated, diffuse radiation above the canopy is set to zero, thus not reaching the canopy nor the earth surface. By analyzing the discrepancies between DIF and NODIF experiments we will be able to distinguish the contribution of diffuse radiation to the feedbacks between vegetation and clouds, and whether these feedbacks affect the boundary-layer dynamics. Note that all diffuse radiation in our simulations is due to clouds or canopy, as we account for a clear atmosphere with no aerosols. TOT experiments use the same scheme for clouds but not for the canopy, using a one-leaf model called A-gs, explained by Ronda et al. (2001), with one single value for PAR and without calculating any in-canopy radiation profile. Thus, differences between DIF and TOT cannot be attributed to any physical process because different canopy schemes have been used. Instead, changes in the system between the two experiments may be due to how radiation reaching the canopy is managed. Yet this comparison is useful to determine the sensitivity and reliability of our new scheme, and to reaffirm the effects of energy surface partition on the boundary layer and its clouds. Experiments have been repeated with higher LAI=5 to find whether the feedbacks and relations in the boundary layer are affected by LAI variations. A sketch showing the differences between experiments is shown in Figure 2.1. An overview of all the experiments carried out during this thesis is shown in Table 2.1, with the ones selected for further analysis in bold. A detailed table with additional simulation parameters and initial conditions is given in Appendix A.
Table 2.1: Names and experimental setup of all simulations in DALES. Experiments used for further analysis in this thesis are typed in bold. The abbreviations in radiation schemes stand for Simple Radiation scheme (RS), and delta-Eddington scheme (DE), respectively. The abbreviations in the Radiation-cloud interactions stand for aggregated treatment of diffuse and direct radiation (Agg), explicit treatment of direct and diffuse radiation (Dir, Dif) and no presence of clouds (No clouds), respectively.

<table>
<thead>
<tr>
<th>Experiment name</th>
<th>Radiation scheme</th>
<th>LAI</th>
<th>Radiation-cloud interaction</th>
<th>Canopy-leaf scheme</th>
<th>Simulation time (h)</th>
<th>Domain size (x x y x z) (Km)</th>
<th>Other remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>S2S</td>
<td>3, SR</td>
<td>2</td>
<td>Agg</td>
<td>A-gs single leaf</td>
<td>10</td>
<td>12 x 12</td>
<td></td>
</tr>
<tr>
<td>S5S</td>
<td>3, SR</td>
<td>5</td>
<td>Agg</td>
<td>A-gs single leaf</td>
<td>10</td>
<td>12 x 12</td>
<td></td>
</tr>
<tr>
<td>E2S (TOT)</td>
<td>2, DE</td>
<td>2</td>
<td>Dir, Dif</td>
<td>A-gs single leaf</td>
<td>10</td>
<td>12 x 12</td>
<td></td>
</tr>
<tr>
<td>E5S (TOT5)</td>
<td>2, DE</td>
<td>5</td>
<td>Dir, Dif</td>
<td>A-gs single leaf</td>
<td>10</td>
<td>12 x 12</td>
<td></td>
</tr>
<tr>
<td>E2D (DIF)</td>
<td>2, DE</td>
<td>2</td>
<td>Dir, Dif</td>
<td>A-gs double leaf</td>
<td>10</td>
<td>12 x 12</td>
<td></td>
</tr>
<tr>
<td>E5D (DIF5)</td>
<td>2, DE</td>
<td>5</td>
<td>Dir, Dif</td>
<td>A-gs double leaf</td>
<td>10</td>
<td>12 x 12</td>
<td></td>
</tr>
<tr>
<td>N2D</td>
<td>2, DE</td>
<td>2</td>
<td>No clouds</td>
<td>A-gs double leaf</td>
<td>10</td>
<td>12 x 12</td>
<td></td>
</tr>
<tr>
<td>N5D</td>
<td>2, DE</td>
<td>5</td>
<td>No clouds</td>
<td>A-gs double leaf</td>
<td>10</td>
<td>12 x 12</td>
<td></td>
</tr>
<tr>
<td>E2D0 (NODIF)</td>
<td>2, DE</td>
<td>2</td>
<td>Dir, Dif</td>
<td>A-gs double leaf</td>
<td>10</td>
<td>12 x 12</td>
<td>1</td>
</tr>
<tr>
<td>E5D0 (NODIF5)</td>
<td>2, DE</td>
<td>2</td>
<td>Dir, Dif</td>
<td>A-gs double leaf</td>
<td>10</td>
<td>12 x 12</td>
<td>1</td>
</tr>
<tr>
<td>DBL</td>
<td>2, DE</td>
<td>2</td>
<td>Dir, Dif</td>
<td>A-gs double leaf</td>
<td>10</td>
<td>24 x 24</td>
<td></td>
</tr>
<tr>
<td>LC0</td>
<td>2, DE</td>
<td>2</td>
<td>Dir, Dif</td>
<td>A-gs double leaf</td>
<td>14</td>
<td>12 x 12</td>
<td>2</td>
</tr>
<tr>
<td>+15</td>
<td>3, SR</td>
<td>2</td>
<td>Agg</td>
<td>A-gs single leaf</td>
<td>10</td>
<td>12 x 12</td>
<td>3</td>
</tr>
<tr>
<td>k07</td>
<td>2, DE</td>
<td>2</td>
<td>No clouds</td>
<td>A-gs double leaf</td>
<td>10</td>
<td>12 x 12</td>
<td>4</td>
</tr>
<tr>
<td>E2DP</td>
<td>2, DE</td>
<td>2</td>
<td>Dir, Dif</td>
<td>A-gs double leaf</td>
<td>10</td>
<td>12 x 12</td>
<td>5</td>
</tr>
<tr>
<td>E2DS</td>
<td>2, DE</td>
<td>2</td>
<td>Dir, Dif</td>
<td>A-gs double leaf</td>
<td>10</td>
<td>12 x 12</td>
<td>6</td>
</tr>
</tbody>
</table>

1. After calculating direct and diffuse radiation due to clouds, diffuse radiation is neglected (swdif set to 0.01).
2. Corrected bug in zenith calculation, and Cskin=0.
3. Modified solar constant S0=1391.
4. Prescribed $k_{dr} = 0.7$.
5. $P_{PAR_{ag}} = 0.05$.
Chapter 3

Fundamental concepts

The main contributions on this thesis consist of the implementation on DALES, testing and sensitivity analysis of processes sensitive to diffuse radiation. The partition of the incoming shortwave radiation between direct and diffuse is driven by the presence of clouds and canopy. For the interaction in clouds, the delta-Eddington plan-parallel one dimensional radiative transfer model is used (Joseph et al., 1976). For the sub-grid radiation transfer inside the canopy, a new model is proposed inspired in the work by Jacobs and De Bruin (1997) and Spitters (1986). A brief description of the delta-Eddington method is given in the next section, while the features of the canopy radiation transfer model are explained in Section 3.2.

3.1 Delta-Eddington method

3.1.1 Theory

There is a significant difference between the solar radiation reaching the top of the atmosphere and the solar radiation that finally reaches the surface. The reason for this difference is that along its radiative transfer through the atmosphere some radiation is absorbed and scattered back to space. In this work we effectively divide the atmosphere in two layers, separated at a height of 500 hPa. Above that level we consider the free atmosphere, here considered to be a non-polluted Standard Rayleigh atmosphere (Barbaro, 2015). In the free atmosphere we assume Rayleigh scattering to be the dominant process due to the significant amount of molecules present at these altitudes. Since the main interest of the study is to analyze the relation between clouds and the vegetated surface and its implications on the evolution of the Boundary Layer (BL), we evaluate a situation with no aerosols between the 500 hPa level and the surface. Considering the aerosols present on a September day in the boundary layer in continental Brazil, Jiang and Feingold (2006) found a decrease of direct radiation of around 20%. On the other hand, a nearly constant increase of diffuse radiation of about 80 W m$^{-2}$ at the surface was observed and successfully simulated using delta-Eddington method at CESAR (Cabauw Experimental Site for Atmospheric Research) in The Netherlands, by Barbaro et al. (2014). In our case the water
Figure 3.1: Ratio of direct (top) and diffuse (bottom) radiation reaching the ground compared to the radiation present at the top of the boundary layer $SW_{\text{top}}$ for increasing cloud optical depth $\tau$, as obtained by the delta-Eddington method at the terrestrial equator and with asymmetry factor $g = 0.85$ (Barbaro, 2015). The gradual color of the lines shows the dependency on solar zenith angle: red lines stand for zenith angle $\theta = 0^\circ$ and yellow lines for $\theta = 88^\circ$.

droplets inside the clouds, with a prescribed effective radius of $r = 10 \ \mu m$, are the only source of scattering of shortwave radiation below the 500 hPa level. Here we focus on the phenomena below the top of the boundary layer. Thus, we prescribe a constant value of $SW_{\text{ToD}} = 1000 \ \text{W m}^{-2}$ as a top boundary condition in our domain, a representative value for the height of 500 hPa.

The Eddington method for radiative transfer was originally explained in Shettle and Weinman (1970), and later approximated and further developed including a delta function by Joseph et al. (1976). This method has been already implemented and successfully tested in DALES for aerosols by Barbaro (2015). Furthermore, some simple cases have been analyzed using this method for boundary-layer clouds in order to endure its consistency.

The solutions for the delta-Eddington method read:

\[
SW_{\text{dif}}^\uparrow = I_0 - \frac{2}{3}I_1 \\
SW_{\text{dif}}^\downarrow = I_0 + \frac{2}{3}I_1 \\
SW_{\text{dir}}^\downarrow = \mu F_0 e^{-\tau_i}/\mu
\]  

where $\tau_i'$ refers to the corrected optical (cloud) depth in the $i$-th horizontal layer, $SW$ stands for (upwards $\uparrow$ or downwards $\downarrow$ and direct $\text{dir}$ or diffuse $\text{dif}$) shortwave radiation, $\mu = \cos \theta$
and $\theta$ is the zenith angle. $I_0$ and $I_1$ are defined so that $I_d(\tau) = I_0(\tau) + \mu I_1(\tau)$, where $I_d$ is the total diffuse radiation (Shettle and Weinman, 1970). It must be noted that concerning the delta-Eddington method, we assumed the sun to be always overhead. Thus, although we account for the variation in solar radiation intensity over the day, we assume the shadow of the clouds to be always right under the cloud. This is a reasonable approximation since any asymmetry due to shadow for non-zero solar zenith angle has only very small impact on the turbulent motion field (Schumann et al., 2002).

For a complete explanation and derivation of this method, the reader is referred to Joseph et al. (1976) for the delta-Eddington approximation and to Barbaro (2015) for its application, and to Shettle and Weinman (1970) for the original Eddington method.

As expected from Equations (3.2) and (3.3), the amount of shortwave radiation reaching the surface is directly related to the magnitude of the cloud optical depth $\tau$. Figure 3.1 shows an exponential-like decrease in shortwave direct radiation, as it was stated in Eq. (3.3). The diffuse component of SW is somehow more complex to explain, although still physically consistent: there is a solar-angle dependent maximum for $\tau$ between $\tau = 1$ and $\tau = 10$, since growing cloud thickness converts more direct to diffuse radiation while at the same time reduces the overall radiation going through the cloud. This feature can be of critical importance for the feedbacks and interactions in our model, since the shallow cumulus clouds created during the day will, at least at a certain moment, have an optical depth of between 1 and 10. What is more, McFarlane and Grabowski (2007) showed that in the tropics the optical depth of the most common shallow cumulus ranges between $\tau = 5 - 10$, a finding also supported by Slawinska et al. (2008). To our knowledge, a study like this has not been carried out for mid-latitude shallow cumulus. Accounting for the diffuse radiation generated under shallow cumulus clouds is something that was not done with the previous scheme, and will be considered with the delta-Eddington scheme.

3.1.2 Impact of delta-Eddington at the surface

The presence and thickness of clouds is the main driver for the variations in direct and diffuse light reaching the surface, as shown in previous section. At the same time, the creation of clouds is influenced by the vegetation-driven fluxes at the surface (Vilà-Guerau de Arellano et al., 2014). It is important to remark that the clouds have an immediate impact at the surface. Plots above in Fig. 3.2 show the direct effects of delta-Eddington equations (Eqs. (3.2) and (3.3)): we see how clouds, characterized by their optical depth $\tau$ (Fig. 3.2a), reduce the amount of downwards shortwave radiation $SW_{dir}$ at the surface (3.2b). At some points ($x=3.8, y=4$), there is none or almost no direct radiation reaching the surface. Meanwhile, diffuse radiation $SW_{dif}$ (Fig. 3.2c) is positive at points where $\tau$ is larger than 0. As shown in Fig. 3.1, maximum values for $SW_{dif}$ are present where $\tau$ ranges between 0 and 10. Note that under these conditions values for diffuse radiation can actually be higher than for direct radiation ($x=2.1, y=8.1$). Plots below in Figure 3.2 show the immediate response of the surface to these heterogeneities. Figure 3.2d shows that photosynthesis rates can plummet to 0 under thick enough clouds (at $x=3.8, y=4$). On the other hand and under certain conditions, values of $A_n$ can be actually higher under a cloud than under clear sky ($x=0.5, y=8$). This can happen because, although there is less light reaching the surface, the highest absorption efficiency of diffuse radiation by the canopy can overcome these reduction on aggregated light. The sensitivity of the canopy photosynthesis to direct/diffuse ratio light will be further analyzed in Section 4.1.1. Finally, the heterogeneities at the surface
Figure 3.2: Instantaneous horizontal cross sections of optical depth $\tau$, downwards shortwave direct radiation $SW_{\text{dir}}$ at the ground, downwards shortwave diffuse radiation $SW_{\text{dif}}$ at the ground, photosynthesis rate $A_n$, latent heat flux $LE$, and sensible heat flux $SH$ at 15:47 LT in the numerical experiment DIF.

due to clouds above will also affect the surface fluxes. As seen in Fig. 3.2e, the latent heat flux $LE$ can vary from 0 to 150 Wm$^{-2}$ only due to cloud-induced heterogeneities, while sensible heat flux $SH$ ranges from negative values to 200 Wm$^{-2}$ (3.2f).

### 3.2 Representing radiation transfer inside the canopy

Current subcloud layer models are able to calculate carbon assimilation and photosynthesis rates, as well as surface resistances for a "single leaf" surface. However, this approach loses its realism when a canopy is present at the surface because of the different radiation transfer properties inside the canopy for both direct and diffuse PAR or, more in general, radiation. This fact becomes especially relevant for the current study, where both diffuse and direct radiation components may be present at the top of the canopy. The purpose of this section is to explain the theory and implementation of the canopy radiation and photosynthesis scheme inspired in the code used by Jacobs and De Bruin (1997) and in the article by Spitters (1986). Values for conductance and assimilation representing the whole canopy will be obtained accounting for different assimilation rates at leaf level depending on the height inside the canopy. It must be kept in mind, however, that our representation considers that radiation is the only variable changing throughout the canopy, assuming other dynamic variables such as temperature, water vapor deficit or CO2 concentrations to be equal throughout the canopy. The relevance of the proposed parametrization lies on the higher computational efficiency obtained by such a model,
Figure 3.3: Representation of the transfer of direct and diffuse radiation inside the canopy. The three levels at which primary productivity and CO$_2$ stomatal conductance are calculated are shown, as well as the sunlit (full line box) and shaded leave (dashed line box) distinction and the radiation lost by reflection and scattering effects (blue lines). Full and dashed arrows represent direct and diffuse light, respectively. Interestingly, a stronger attenuation in radiation is shown for the direct radiation compared to the diffuse one. The sketch shows the secondary diffuse component coming from scattered direct radiation at each level (dashed black arrows going from direct to diffuse light), and the tertiary diffuse component originated after the reflection of the direct beam in the ground surface (red dashed lines).

compared to a more complex and time consuming full canopy multi-layer model resolving all the dynamic variables at each canopy level. That multilayer approach is more convenient for higher canopies such as tall vegetation.

3.2.1 Model description

The main concepts of the parametrization are sketched in Figure 3.3. The model takes into account the following processes: transmission of radiation by leaves, scattering of direct radiation by leaves, absorption of radiation by leaves and upward reflection of direct and diffuse radiation by ground surface. The calculation of photosynthesis rate and conductance for the whole canopy is carried out in three steps. Firstly, the potential leaf absorption of direct and diffuse light at leaf level is calculated at different heights, taking into account secondary (direct light scattered and converted into diffuse) and tertiary (diffuse and direct light reflected by the ground as upward diffuse radiation) diffuse sources. All direct light not initially absorbed by leaves is assumed to be either lost or converted by ground reflection and leaf scattering processes into diffuse radiation. The diffuse and direct absorbed quantities are redistributed in absorption values by sunlit and shaded leaves for each level, leading to a net photosynthesis rate and stomatal conductance value for each level. Finally, the scaling up from leaf level to whole canopy is carried out. There, the contributions of each level to total photosynthesis rate are added using the Gaussian integration method described in Goudriaan (1986).
Step 1: PAR profiles and absorption at leaf level at a given canopy height

Shortwave radiation and Photosynthetically Active Radiation are closely related. In the literature a reduction factor around 0.5 is used to obtain the PAR from the shortwave incoming radiation (Alados and Alados-Arboledas, 1998; Spitters et al., 1986). Therefore, this factor is used for obtaining values of incoming PAR at the top of the canopy, both for direct \( (PAR_{ToC}^{dr}) \) and diffuse \( (PAR_{ToC}^{df}) \) components. The shortwave diffuse and direct components from which we obtain the PAR components are calculated by the delta-Eddington method (Shettle and Weinman, 1970), as mentioned in Section 3.1. In general, radiation is reduced exponentially when it penetrates into the canopy according to the Beer-Lambert law as follows:

\[
SW(D) = (1 - c)SW^{ToC}e^{-k iLAI(D)} \tag{3.4}
\]

where \( SW^{ToC} \) stands for the radiation at the top of the canopy, \( k \) is the extinction coefficient and \( c \) is a factor accounting for loses of radiation due to scattering or reflection, depending on the type of radiation. \( iLAI(D) \) \( \left[ m_{\text{leaf}}^2 m_{\text{ground}}^{-2} \right] \) is calculated by \( iLAI = LAI D \) and represents the accumulated LAI at depth \( D \), where \( D \) is a value between 0 (canopy top) and 1 (canopy bottom) giving the fraction of total LAI that is above that level. Note that \( D \) will only be equal to the fraction of physical depth if the LAI is uniformly distributed over all the canopy layers. Here, \( SW(D) \) as well as \( SW^{ToC} \) are given in W \( m^{-2} \).

The extinction coefficients for direct and diffuse light are obtained as follows:

\[
k_{df} = k_{dfbl}\sqrt{1 - \sigma} = 0.8\sqrt{1 - \sigma} \tag{3.5}
\]

and

\[
k_{dr} = k_{drbl}\sqrt{1 - \sigma} = \frac{0.5}{\sin \beta}\sqrt{1 - \sigma} \tag{3.6}
\]

where \( k_{df} \) and \( k_{dr}, \left[ m_{\text{ground}}^2 m_{\text{leaf}}^{-2} \right] \) are the extinction coefficients for diffuse \( (df) \) and direct \( (dr) \) components of PAR respectively, and the additional \( bl \) subscript stands for the extinction coefficient of black leaves not transmitting nor reflecting light, but only absorbing (Goudriaan, 1977). \( \beta \) is the solar elevation angle above the horizon. Only scattering in the vertical direction is considered, represented by \( \sigma \) and set to 0.2 (Spitters, 1986). Note that the extinction coefficients are not dimensionless. To endure unit consistency, the combination of factors in the exponential in Eq. (3.4) needs to be dimensionless. It must be noted that \( k_{dr} \) does NOT give the extinction rate of direct light, but the extinction rate of radiation at a certain level due to the direct PAR reaching the top of the canopy. This amount of radiation present at that level may be pure direct or have a secondary or tertiary diffuse component if on the way it was scattered by leaves or the ground, respectively. It may seem straightforward, but it has important implications, because \( k_{dr} \) stands for the extinction rate of the sum of primary direct radiation and the secondary diffuse radiation created when direct radiation is scattered, while \( k_{drbl} \) only takes into account the direct component of radiation.

After defining the different extinction coefficients the behavior of Photosynthetically Active Radiation with canopy depth can be quantified. The amount of PAR is reduced when it penetrates into the canopy, very similarly to how it was stated for radiation in Eq. (3.4). Actually, the relation between intensity and PAR is given, as explained before, by: \( PAR = 0.5 \ SW^{1} c_{veg} \), where \( c_{veg} \) is the surface fraction covered by vegetation. This \( c_{veg} \) is actually a current bug in DALES, since the PAR reaching the surface will not depend on the amount of vegetation, and
will be fixed in the next DALES version. The profile of available PAR [W m\(^{-2}\)] inside the canopy is given, as stated by Spitters (1986) (Eqs. 3 and 4), by:

\[
PAR_{\text{df}}^T(D) = (1 - \rho)PAR_{\text{ToC}}^{\text{df}} e^{-k_{\text{df}}}iLAI(D)
\]

\[
PAR_{\text{dr}}^T(D) = (1 - \rho_{\text{dr}})PAR_{\text{ToC}}^{\text{dr}} e^{-k_{\text{dr}}}iLAI(D)
\]

\[\rho\] stands for the reflection coefficient for horizontally distributed green leaves and for visible light (Goudriaan, 1977, Eq. 2.21), and \[\rho_{\text{dr}}\] for the reflection coefficient for spherically distributed green leaves under direct visible radiation. \(PAR_{\text{df}}^{\text{ToC}}\) and \(PAR_{\text{dr}}^{\text{ToC}}\) give the amount of diffuse and direct radiation, respectively, reaching the top of the canopy. The reflection coefficients used above are defined as:

\[
\rho = \frac{1 - \sqrt{1 - \sigma}}{1 + \sqrt{1 - \sigma}}
\]

\[
\rho_{\text{dr}} = \frac{\rho \frac{2}{1 + 1.6 \sin(\beta)}}{1 \frac{1 + 1.6 \sin(\beta)}{1}} = \frac{1 - \sqrt{1 - \sigma}}{1 + \sqrt{1 - \sigma}} \frac{2}{1 + 1.6 \sin(\beta)}
\]

For diffuse radiation a horizontal leaf distribution is used due to the isotropy of diffuse light. In other words, there is no direction in which diffuse light would not arrive perpendicularly to the leaf, regardless of the distribution (Spitters, 1986). For direct radiation, however, a spherical distribution is assumed and there is a certain angle depending on the leaf orientation with which radiation hits the leaves. The reflection dependency on the sun angle is given by the extra factor in \[\rho_{\text{dr}}\] that was not included in \[\rho\].

Equations (3.7) and (3.8) can be extended by taking into account the light reflected by the ground, which is significant under low LAI. Actually, (Goudriaan, 1977) stated that above a LAI of 2 the influence of the soil surface can be practically neglected. In general, the profile of radiation reflected by the ground is given by:

\[
I_{\text{refl}}(D) = (1 - \text{ref})I_{\text{ground}} e^{-k(LAI-iLAI(D))}
\]

where \(I_{\text{ground}}\) is the radiation reflected by the ground and is calculated by: \(I_{\text{ground}} = aI^{\text{ToC}} e^{-kLAI}\), where \(a\) is the albedo of the surface.

Using this approach for both direct and diffuse radiation we obtain the following profiles:

\[
PAR_{\text{df}}^{\text{refl}}(D) = (1 - \rho)PAR_{\text{df}}^{\text{ground}} e^{-k_{\text{df}}(LAI-iLAI(D))}
\]

\[
PAR_{\text{dr}}^{\text{refl}}(D) = (1 - \rho)PAR_{\text{dr}}^{\text{ground}} e^{-k_{\text{dr}}(LAI-iLAI(D))}
\]

where \(PAR_{\text{df}}^{\text{ground}} = aPAR_{\text{df}}^{\text{ToC}} e^{-k_{\text{df}}LAI}\) and \(PAR_{\text{dr}}^{\text{ground}} = aPAR_{\text{dr}}^{\text{ToC}} e^{-k_{\text{dr}}LAI}\) represent the radiation reflected by the ground surface due to the diffuse and direct radiation at the top of the canopy, respectively. \(PAR_{\text{df}}^{\text{refl}}(D)\) and \(PAR_{\text{dr}}^{\text{refl}}(D)\) can be seen as sources of diffuse light going from the surface upwards with intensity decreasing exponentially with (inverse) canopy depth. The albedo of the ground surface is represented by \(a\), usually estimated as \(a = 0.25\) for grass.
Taking this into account, the extended Equations (3.7) and (3.8) read:

\[ \text{PAR}_{\text{df}}(D) = \text{PAR}_{\text{df}}^T(D) + \text{PAR}_{\text{df}}^{\text{refl}}(D) \]  
\[ \text{PAR}_{\text{dr}}(D) = \text{PAR}_{\text{dr}}^T(D) + \text{PAR}_{\text{dr}}^{\text{refl}}(D) \]  

The second terms in Eqs. (3.14) and (3.15) account for the radiation that is reflected by the ground surface.

It must be recalled that the PAR at the top of the canopy already has diffuse and direct components calculated by the delta-Eddington method. The outcome of Eqs. (3.14) and (3.15) is NOT necessarily the profile inside the canopy of diffuse and direct PAR respectively. Instead, \( \text{PAR}_{\text{df}}(D) \) must be understood as the amount of (diffuse) PAR at normalized canopy depth \( D \) due to the diffuse PAR present at the top of the canopy, and \( \text{PAR}_{\text{dr}}(D) \) as the amount of (diffuse and direct) PAR at normalized canopy depth \( D \) due to the direct PAR present at the top of the canopy. This is more clearly understood considering some assumptions made in this model: the direct PAR has only one primary source, that is, the direct PAR coming from the direct shortwave radiation. For diffuse PAR, however, there are 3 sources assumed: the primary source, that is the background radiation or diffuse radiation coming from above the canopy; the secondary diffuse radiation source, that is the diffuse radiation created when the direct radiation is reflected by leaves; and the tertiary diffuse radiation source, that is the diffuse radiation created after both the direct and diffuse radiation reaching the surface are reflected by the ground. Taking these into account, we can understand Equations (3.14) and (3.15) as follows: Equation (3.14) calculates the amount of diffuse PAR at every level due to the incoming diffuse PAR at the top of the canopy, since no direct radiation is created in the process. It accounts for part of the tertiary diffuse radiation, that is the diffuse radiation reaching the ground and reflected upwards. Equation (3.15) gives the sum of direct, secondary and tertiary diffuse PAR at every level due to the incoming direct PAR at the top of the canopy. Therefore, the diffuse PAR at a level \( D \) will have contributions from both \( \text{PAR}_{\text{df}}^T(D) \) and \( \text{PAR}_{\text{dr}}^T(D) \), while the direct PAR will be a fraction of \( \text{PAR}_{\text{dr}}(D) \) at that level, since some of the PAR accounted for will be secondary or tertiary diffuse.

The total profile for PAR direct radiation can be actually given by Equation 5 in Spitters (1986):

\[ \text{PAR}_{\text{dr}}^{\text{prof}}(D) = (1 - \rho_{\text{dr}})(1 - \sigma)\text{PAR}_{\text{dr}}^{\text{C}}e^{-k_{\text{dr}}\text{LAI}(D)} \approx (1 - \sigma)\text{PAR}_{\text{dr}}^{\text{C}}e^{-k_{\text{dr}}\text{LAI}(D)} \]  

which only considers the direct PAR present at each level due to the direct PAR at the top of the canopy, without considering the secondary diffuse radiation nor any radiation reflected by the ground surface. The factor \( (1 - \sigma) \) accounts for the fact that some of the available direct radiation will be scattered by the leaves. The approximation done in the second equality is due to the fact that \( \rho_{\text{dr}} \) is of the order of 0.05. Therefore, the factor giving the loses due to reflection and scattering can be approximated to \( (1 - \sigma) \). The exponential \( e^{-k_{\text{dr}}\text{LAI}(D)} \) can also be understood as the fraction of sunlit leaves at that level \( D \).

Then, the diffuse PAR profile could be given, as suggested by Spitters (1986) by:
Figure 3.4: In-canopy profiles for Photosynthetic Active Radiation (left), stomatal conductance $g_c$ (center) and primary productivity $A_g$ (right) for a canopy with LAI=2 and top-of-canopy radiation consisting on $PAR_{ToC}^T = 250 \text{ W m}^{-2}$ and $PAR_{ToC}^{dr} = 50 \text{ W m}^{-2}$ at the equator and solar elevation angle $\beta = \frac{\pi}{2}$. The plot on the left shows the total amount of direct (solid red) and diffuse (solid green) PAR at each height. Red dotted and green dotted lines show direct and diffuse radiation, respectively, reflected by the ground. Green dashed line gives the secondary diffuse radiation at each level. Light and dark blue lines give the contribution of sunlit and shaded leaves, respectively, to the net values $g_c^{net}$ and $A_g^{net}$ in black. The three levels that are actually calculated and used in the model are shown by gray horizontal dashed lines.

$$PAR_{df}^{prof}(D) = PAR_{df}^T(D) + PAR_{dr}^T(D) - PAR_{dr}^{prof}(D)$$  \hspace{1cm}(3.17)$$

A graphical example of Eqs. (3.16) and (3.17) is shown in Figure 3.4a.

In general, the absorption of irradiance per unit leaf area $H(D) \text{ [W m}^{-2} \text{]}$ will be a fraction of the irradiance arriving $I(D)$ given in Equation (3.4), and it can be calculated as:

$$H(D) = - \frac{dI(D)}{dLAI} = (1 - ref)k I_{ToC} e^{-kLAID} = kI(D)$$  \hspace{1cm}(3.18)$$

The absorption at a level can be calculated as the difference between the radiation reaching that level and the radiation reaching the next (inferior) level. This definition, in fact, is nothing but the discrete definition of a derivative. Note that for this absorption and all the absorptions defined here the units are W m$^{-2}$ leaf, while the previously defined PAR’s were calculated in W m$^{-2}$ ground.
The total absorption due to diffuse PAR at the top of the canopy per unit leaf area at a certain LAI-normalized depth $D$ follows from Eqs. (3.14) and (3.18), and is given by:

$$H_{df}^T(D) = -\left( \frac{d\text{PAR}_{df}^T(D)}{d\text{iLAI}} + \frac{d\text{PAR}_{df}^{refl}(D)}{d(-\text{iLAI})} \right)$$

$$= (1 - \rho)k_{df}\text{PAR}_{df}^{ToC}e^{-k_{df}\text{iLAI}(D)} + (1 - \rho)k_{df}\text{PAR}_{df}^{ground}e^{-k_{df}(LAI-\text{iLAI}(D))} + k_{df}\text{PAR}_{df}^{refl}(D)$$

(3.19)

Note that in this case the second term has been differentiated over $-\text{iLAI}$. This is because the radiation reflected by ground travels upward, from the ground to the top of canopy.

Similarly, for the total absorption per unit leaf area due to direct PAR at the top of the canopy, combining Eqs. (3.15) and (3.18):

$$H_{dr}^T(D) = -\left( \frac{d\text{PAR}_{dr}^T(D)}{d\text{iLAI}} + \frac{d\text{PAR}_{dr}^{refl}(D)}{d(-\text{iLAI})} \right)$$

$$= (1 - \rho_{dr})k_{dr}\text{PAR}_{dr}^{ToC}e^{-k_{dr}\text{iLAI}(D)} + (1 - \rho)k_{df}\text{PAR}_{dr}^{ground}e^{-k_{df}(LAI-\text{iLAI}(D))} + k_{dr}\text{PAR}_{dr}^{refl}(D)$$

(3.20)

The primary absorption per unit leaf area of the direct component of the direct PAR at the top of the canopy is given by:

$$H_{dr}^{prof}(D) = -\frac{d\text{PAR}_{dr}^{prof}(D)}{d\text{iLAI}} = (1 - \sigma)k_{drbl}\text{PAR}_{dr}^{ToC}e^{-k_{drbl}\text{iLAI}(D)}$$

(3.21)

Later we will be interested in knowing the amount of absorbed radiation by shaded and sunlit leaves separately, so we can finally add their contributions depending on the amount of sunlit and shaded leaves per layer. Therefore, it is interesting to calculate the amount of radiation absorbed at horizontal leaf level if we only take into account the direct light coming from the sun. It is sensible to assume that, in this case, the amount of radiation will not depend on LAI, since the beam would hit the leaf with equal intensity regardless of the number of leaves lying above. If all the direct radiation hitting a squared meter of ground was absorbed, this amount would be given by $(1 - \sigma)\text{PAR}_{dr}^{ToC}$. However, a fraction $e^{-k_{drbl}LAI}$ reaches the ground and, therefore, it is not absorbed as direct radiation. Thus, the total direct radiation absorbed per meter square of ground is $(1 - \sigma)\text{PAR}_{dr}^{ToC}(1 - e^{-k_{drbl}LAI})$. The total area of sunlit leaves per meter square of ground $A_{\text{sun}}$ can be calculated by integrating the already mentioned fraction of sunlit leaves at a level $D (e^{-k_{drbl}\text{iLAI}(D)})$ over all canopy depth or, what is the same, over LAI. By doing so:

$$A_{\text{sun}} = \int_0^{LAI} e^{-k_{drbl}\text{iLAI}(D)} \text{dLAI} = \frac{1}{k_{drbl}}(1 - e^{-k_{drbl}LAI})$$

(3.22)
Now, we can easily calculate the amount of radiation absorbed per sunlit leaf area by dividing the absorbed radiation per meter square ground by the area of sunlit leaves in a meter square ground:

\[
H_{PP}^{dr} = \frac{(1 - \sigma) \text{PAR}^C_\text{dr} (1 - e^{-kd_{drbl}LAI})}{k_{drbl} (1 - e^{-kd_{drbl}LAI})} = (1 - \sigma) k_{drbl} \text{PAR}^C_\text{dr}
\] (3.23)

The units of \(H_{PP}^{dr}\) are W m\(^{-2}\) leaf per, where leaf per stands for leaves perpendicular to the beam, and therefore consistent with the absorbed quantities defined before. Note, as expected and stated by Spitters (1986), that "the intensity of the direct beam per unit leaf area does not change with canopy depth".

Now that we have expressions for direct and diffuse PAR absorptions at each level, we will calculate the absorption by sunlit and shaded leaves at each level. Shaded leaves will absorb primary, secondary and tertiary diffuse radiation, while sun leaves will additionally absorb the no scattered primary direct light.

To account for the radiation absorbed by shaded leaves per leaf area at any level, the simplest but still accurate enough method is to calculate it as the difference between the total absorption at that level (diffuse light absorption accounting for ground reflection of diffuse light + direct light absorption accounting for secondary and tertiary diffuse absorption) minus the primary direct absorption at that level (without secondary or tertiary diffuse radiation source):

\[
H_{shad}(D) = H_{Tdf}(D) + H_{Tdr}(D) - H_{prof}(D)
\] (3.24)

To obtain the total absorption of sun leaves \(H_{sun}(D)\), we need to add the primary absorption per unit leaf area coming from the sun to the term obtained in Eq. (3.24). This primary absorption term will depend on the angle between the incident beam and the leaf position and, therefore, on the leaf angle distribution of the canopy. Jacobs and De Bruin (1997) proposed a spherical leaf distribution (=not preferred leaf orientation). Strictly speaking, an explicit calculation requires the integration over all the angles in order to account for the direct beam incident on every leaf. However, as shown in Goudriaan (1988), taking 3 angles is enough for an accurate estimation of assimilation by direct beam irradiation by means of a Gaussian integration. In this method, few points (three angles, in this case) are taken representing the whole canopy and they are added taking into account some predefined weighting factors (Goudriaan, 1986). The 3 angles are chosen such that the sinus of each of them are \(\sin(\gamma_1) = 0.1127\), \(\sin(\gamma_2) = 0.5000\), and \(\sin(\gamma_3) = 0.8873\) respectively. The weights are given as follows: \(w_1 = w_3 = 0.2778\), and \(w_2 = 0.4444\). These same values will be used for the other Gaussian integration carried out in the upscaling in Section 3.2.1. Therefore, to obtain the absorbed radiation per leaf area by sunlit leaves with a certain incidence angle \(\gamma\):

\[
H_{sun}(D, \gamma_i) = H_{shad}(D) + H_{PP}^{dr} \frac{\sin(\gamma_i)}{\sum_{i=1}^{3} w_i \sin(\gamma_i)}
\] (3.25)

Note that following Einstein notation, the equation above splits into three equations, since the
angle will have one of the three values showed above for each equation. The last term in Eq. (3.25) is divided over the product of all the weights with their respective sinus in order to fulfill the conservation of energy per square meter ground. A detailed explanation on the derivation of Eq. (3.25) is given in Appendix B. Note that the units of $H_{sun}$ are W m$^{-2}$, where leaf area is not perpendicular to the light beam but tilted with an inclination given by the angle $\gamma_i$.

**Step 2: Gross primary productivity and conductance by sunlit and shaded leaves at a given canopy height**

Once we have the radiation absorbed per unit leaf area by shaded leaves we can obtain the CO$_2$ gross primary productivity $A_{g,l}(D)$ [mg s$^{-1}$ m$^{-2}$ shaded leaf] and CO$_2$ stomatal conductance $g_{c,l}(D)$ [mm s$^{-1}$] of shaded leaves per unit leaf area at leaf level using the the A-gs method (Jacobs and De Bruin, 1997; Ronda et al., 2001). In general the gross primary productivity at leaf level $A_{g,l}^*(D)$ under unstressed water situations is calculated as:

$$A_{g,l}^*(D) = (A_m + R_d)[1 - e^{-\frac{\alpha H(D)}{A_m + R_d}}]$$  \hspace{1cm} (3.26)

Here, $A_m$ stands for the primary productivity or photosynthetic rate at infinite light, $R_d$ [mg s$^{-1}$ m$^{-2}$ shaded leaf] represents the dark autrophic respiration and is calculated by $R_d = 0.11A_m$. The light use efficiency is given by $\alpha$. Additionally, this value is corrected by a stress function $f(w)$, which accounts for the moisture content in the soil. This function is defined as:

$$f(w) = \max \left[ 0, \min \left( 1, \frac{\bar{w} - w_{wilt}}{w_{fc} - w_{wilt}} \right) \right]$$  \hspace{1cm} (3.27)

where $w_{fc}$ and $w_{wilt}$ stand for the soil moisture content at field capacity and wilting point, respectively. Therefore, the moisture-corrected gross primary productivity at leaf level is:

$$A_{g,l}(D) = f(w)A_{g,l}^*(D) = f(w)(A_m + R_d)[1 - e^{-\frac{\alpha H(D)}{A_m + R_d}}]$$  \hspace{1cm} (3.28)

Now, we have enough information to calculate the CO$_2$ conductance at leaf level $g_{c,l}$, that is calculated using the following expression:

$$g_{c,l}(D) = g_{min,c} + \frac{A_{g,l}(D)}{(C_s - C_i)}$$  \hspace{1cm} (3.29)

where $C_s$ and $C_i$ are the external or atmospheric and internal or intercellular CO$_2$ concentrations respectively. $g_{min,c}$ is the minimal cuticular conductance for carbon given by $g_{min,c} = \frac{g_{min,w}}{15}$, where $g_{min,w}$ stands for the minimal cuticular conductance for water and assumed to be $g_{min,w} = 2.5$ mm s$^{-1}$ (Ronda et al., 2001). In reality, variables like $C_s$ or $C_i$ are dependent on the temperature and water vapor deficit, which vary inside the canopy. However, as state at the beginning of this section, we assume all dynamic variables to be equal inside the canopy except PAR.

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For a more detailed explanation on Eqs. (3.26)-(3.29) and definition of variables the reader is referred to Vilà-Guerau de Arellano et al. (2015).

To calculate the primary productivity at leaf level by shaded leaves $A_{g,l}^{shad}(D)$, Eq. (3.28) must be used, but using $H^{shad}(D)$ instead of $H(D)$. After doing this, the expression for $A_{g,l}^{shad}(D)$ is given by:

$$A_{g,l}^{shad}(D) = f(w)(A_m + R_d)[1 - e^{-\alpha H^{shad}(D)/A_m + R_d}]$$  \hfill (3.30)

For CO$_2$ conductance of shaded leaves at leaf level $g_{c,l}^{shad}$ [mm s$^{-1}$], Eq. (3.29) changes to:

$$g_{c,l}^{shad}(D) = g_{min,c} + A_{g,l}^{shad}(D) (C_s - C_i)$$  \hfill (3.31)

The leaf-angle dependent CO$_2$ gross primary productivities for sunlit leaves at leaf level $A_{g,l}^{sun}(D,\gamma_i)$ [mg s$^{-1}$ m$^{-2}$ leaf]$_i$ where leaf$_i$ means a leaf with inclination given by $\gamma_i$, and CO$_2$ conductance $g_{c,l}^{sun}(D,\gamma_i)$ [mm s$^{-1}$] are first calculated for each angle using analogous expressions to those in Eqs. (3.30) and (3.31) respectively. In these cases, the expressions read:

$$A_{g,l}^{sun}(D,\gamma_i) = f(w)(A_m + R_d)[1 - e^{-\alpha H^{sun}(D,\gamma_i)/A_m + R_d}]$$  \hfill (3.32)

$$g_{c,l}^{sun}(D,\gamma_i) = g_{min,c} + A_{g,l}^{sun}(D,\gamma_i) (C_s - C_i)$$  \hfill (3.33)

Afterwards, the gross primary productivities $A_{g,l}^{sun}(D)$ [mg s$^{-1}$ m$^{-2}$ leaf]$_p$ and conductance $g_{c,l}^{sun}(D)$ [mm s$^{-1}$] of sunlit leaves accounting for the spherical leaf distribution are obtained, adding each term according to the Gaussian weights displayed before Eq. (3.25) ($w_1 = w_3 = 0.2778, w_2 = 0.4444$) and as explained in Goudriaan (1986):

$$A_{g,l}^{sun}(D) = w_1 A_{g,l}^{sun}(D,\gamma_1) + w_2 A_{g,l}^{sun}(D,\gamma_2) + w_3 A_{g,l}^{sun}(D,\gamma_3)$$  \hfill (3.34)

$$g_{c,l}^{sun}(D) = w_1 g_{c,l}^{sun}(D,\gamma_1) + w_2 g_{c,l}^{sun}(D,\gamma_2) + w_3 g_{c,l}^{sun}(D,\gamma_3)$$  \hfill (3.35)

It is easy to see that the weights are projecting the addends from their different leaf orientations gamma, on the perpendicular-to-beam leaf orientation.

Once we have the gross primary productivity and conductance per leaf area of shaded and sunlit leaves separately, they are added taking into account the fraction of sunlit leaf area at that level $e^{-k_{delt}LAI(D)}$. The gross primary productivity $A_g^{net}(D)$ [mg s$^{-1}$ m$^{-2}$] and conductance $g^{net}(D)$ [mm s$^{-1}$], still per unit leaf area at one level are given by:

$$A_g^{net}(D) = A_{g,l}^{sun}(D)e^{-k_{delt}LAI(D)} + A_{g,l}^{shad}(D)(1 - e^{-k_{delt}LAI(D)})$$  \hfill (3.36)
\[ g^{\text{net}}_c(D) = g^{\text{sun}}_c(D)e^{-k_3,i\text{LAI}(D)} + g^{\text{shad}}_c(D)(1 - e^{-k_3,i\text{LAI}(D)}) \]  

(3.37)

A graphical example of Eqs. (3.36) and (3.37) is shown in Figures 3.4c and 3.4b, respectively. This Figure shows the increasing relevance of secondary and tertiary radiation with canopy depth.

Step 3: Upscaling of gross primary productivity and conductance for canopy

In order to obtain the values of \( A_g \) and \( g_c \) not for one level but for the whole canopy per ground unit, the functions (3.36) and (3.37) should be integrated over the canopy height and multiplied by LAI in order to obtain the gross primary productivity and conductance per unit ground area. However, as shown in Goudriaan (1986), a Gaussian integration can be done to simplify the procedure. Goudriaan (1986) shows that by using a 3 point Gaussian integration the results do not differ much from more detailed methods. Therefore, three levels \( D_i \) are taken such that \( i\text{LAI}(D_1) = 0.1127 \) LAI, \( i\text{LAI}(D_2) = 0.5000 \) LAI, and \( i\text{LAI}(D_3) = 0.8873 \) LAI with three weights \( v_i \) respectively (0.2778 LAI, 0.4444 LAI, 0.2778 LAI) as used for the angle integration in Section 3.2.1 and explained in Eqs. 20 and 21 in Spitters (1986). This upscaling method using gaussian weights has also been adopted by European Centre for Medium-Range Weather Forecasts (ECMWF) (Boussetta et al., 2013; ECMWF, 2014). Therefore, the final expression for carbon conductance for the whole canopy reads:

\[ A^{\text{can}}_g = \sum_{i=1}^{3} v_i A^{\text{net}}_g(D_i) \]  

(3.38)

\[ g^{\text{can}}_c = \sum_{i=1}^{3} v_i g^{\text{net}}_c(D_i) \]  

(3.39)

Once \( g^{\text{can}}_c \) is obtained, a more realistic value for the net CO\(_2\) flow into the plant at canopy level can be calculated by adding the influence of atmospheric processes, as usually done for evaporation processes at the surface. Here, \( r_a \) represents the aerodynamic resistance to the plant intake. Thus, the net CO\(_2\) flow into the plant at canopy level \( A^{\text{can}}_n \) reads:

\[ A^{\text{can}}_n = \frac{C_s - C_i}{r_a + r_{\text{vegCO}_2}} \]  

(3.40)

where \( r_{\text{vegCO}_2} = \frac{1}{C_i} \). Note that the presence of \( r_a \) will imply a dependance of the plant activity on atmospheric conditions. In fact, \( r_a \) acts as a limiting factor for net CO\(_2\) into the plant, especially for low \( r_{\text{veg}} \) values. The reader may wonder why the values for primary productivity \( A_g \) have been calculated if, eventually, a corrected value is obtained which only needs \( g^{\text{can}}_c \) to be fed in. The reason is that by doing so, we are able to draw approximate in-canopy profiles of the primary productivity (and net assimilation rate, if needed, using \( A_{n,l}(D) = A_{g,l}(D) - R_d \) (Ronda et al., 2001).
3.2.2 Model validation

In order to test the performance and reliability of the model the results have been compared with data from the study by Baldocchi et al. (1985). Part of the step 1 of our model, that is the radiation profiles inside the canopy, has been compared with the measurements obtained in an oak forest and with the predicted profile by two models, the Norman’s radiative transfer model (Norman, 1979, 1982), sharing some features with our model, and the de Wit’s model (de Wit, 1965), as explained in Baldocchi et al. (1985). In short, Norman’s radiative transfer model takes into account direct radiation, coming from the sun; diffuse radiation, coming from an isotropic sky; and radiation scattered by leaves and ground (our secondary and tertiary diffuse, respectively), by using an iterative method. It gives the radiation profile considering this three radiation sources, the leaf angle distribution, and the geometry between the surface and the Sun. De Wit’s model defines first a light distribution function, defined as the probability of a light beam to hit a leaf. This function is dependent on the solar elevation angle and leaf angle distribution. Then, it uses this function to calculate the fractional penetration of direct and diffuse light separately, assuming a uniformly bright sky for the latter case. De Wit assumes 10% of radiation reaching the ground to be scattered upwards, and reflection of radiation in leaves only upwards or downwards. Both de Wit’s and Norman’s methods allow to have as many layers as desired within the canopy.
The measurements were done in an Oak forest. A forest is a more heterogeneous environment concerning the canopy characteristics compared to a crop field or grassland. However, an acceptable agreement is found between Norman’s model and our in-canopy model. The fact that both models predict a not observed increase in diffuse PAR at the top of the canopy (in the range LAI=0 − 1) has been already explained by Baldocchi et al. (1985). When the radiation penetrates in the canopy, some of the direct PAR is scattered and converted into diffuse, increasing the diffuse radiation close to the canopy top. This peak at certain iLAI is comparable to the maximum in diffuse radiation for certain cloud optical depth $\tau$ explained and shown in Fig. 3.1. In reality the top layers of the oak forest show a significant clumping of the leaves, not considered in the model. This clumping facilitates the penetration of direct PAR in the first layers of the canopy and, consequently, less radiation is scattered by leaves and converted to diffuse PAR. The performance of de Wit’s model, clearly miscalculating the amount of diffuse radiation within the canopy, is mostly due to an underestimation of scattering processes (Baldocchi et al., 1985).

More differences in the current comparison can be attributed to the fact that our model shows 5-point daily mean quantities. While the observations were made with a frequency higher than one per minute, only five sun orientations ($\beta = \frac{\pi}{6}$, $\frac{\pi}{3}$, $\frac{\pi}{2}$, $\frac{2\pi}{3}$, $\frac{5\pi}{6}$) were considered for our model, averaging its profiles afterwards. This average, however, is only done for a more fair comparison with observations. For the rest of our research we used instantaneous solar angle values to calculate the radiation profiles. Additionally, we assumed the Plant Area Index used in the article by (Baldocchi et al., 1985), to be the same as Leaf Area Index; and we obtained PAR values from the observed shortwave radiation by the relation $SW = 0.5$ PAR, for both direct and diffuse light.

Note that the profile drawn in Figure 3.5 by our model has more than the three points needed for the Gaussian integration explained in Section 3.2.1 to obtain a more insightful comparison with the profiles given in Baldocchi et al. (1985). For the rest of the research, however, only three points have been taken inside the canopy for radiation, absorption, primary productivity and CO$_2$ stomatal conductance calculations. This is a good approximation, especially for direct PAR, as seen in Fig. 3.5. For diffuse radiation, the performance at the three points where our model is evaluated is not very good. However, it is important to recall that the strength of this method does not lie on its high accuracy, but on an average accuracy combined with a fast and efficient computational performance.


Chapter 4

Results

4.1 Sensitivity analysis

Before fully analyzing the impact of the new model for in-canopy radiation and photosynthesis rate and resistance in DALES, it is convenient to carry out a sensitivity analysis to determine the sensitivity of the system to atmospheric factors like the ratio of direct/diffuse radiation and LAI.

4.1.1 Direct-diffuse ratio

The current radiation parametrization (1LEAF) does not discriminate between direct and diffuse radiation and gives one value for stomatal conductance and net CO$_2$ flow into the plant, calculated at one single leaf (Ronda et al., 2001). The proposed new scheme, however, does distinguish between direct and diffuse radiation, accounting for different canopy penetration rates and other

Table 4.1: Numerical results of the average of simulations for LAI=2. For the simulations with the new method (DIR, DIRDIF, DIFDIR, DIF), the average of five runs, with $\beta = \frac{\pi}{6}, \frac{\pi}{3}, \frac{2\pi}{3}, \frac{5\pi}{6}$ is shown. Between brackets the difference with the current DALES method one-leaf A-gs (1LEAF) is given. Note that the DIF experiment shown here, where we just consider the canopy scheme, is not the same as the DIF experiment analyzed in Section 4, where the role of clouds in radiation is also considered.

<table>
<thead>
<tr>
<th></th>
<th>1LEAF</th>
<th>DIR</th>
<th>DIRDIF</th>
<th>DIFDIR</th>
<th>DIF</th>
</tr>
</thead>
<tbody>
<tr>
<td>$PAR$ (W m$^{-2}$)</td>
<td>300</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$PAR_{\text{DIR}}$ (W m$^{-2}$)</td>
<td>-</td>
<td>300</td>
<td>250</td>
<td>50</td>
<td>0</td>
</tr>
<tr>
<td>$PAR_{\text{DIF}}$ (W m$^{-2}$)</td>
<td>-</td>
<td>0</td>
<td>50</td>
<td>250</td>
<td>300</td>
</tr>
<tr>
<td>$A_n$ (mg m$^{-2}$s$^{-1}$)</td>
<td>0.5392</td>
<td>0.4259 (-27%)</td>
<td>0.4624 (-17%)</td>
<td>0.5397 (+0.09%)</td>
<td>0.5442 (0.9%)</td>
</tr>
<tr>
<td>$g_c$ (mm s$^{-1}$)</td>
<td>$4.460 \times 10^{-3}$</td>
<td>$3.366 \times 10^{-3}$ (-32%)</td>
<td>$3.708 \times 10^{-3}$ (-20%)</td>
<td>$4.465 \times 10^{-3}$ (+0.11%)</td>
<td>$4.511 \times 10^{-3}$ (+1%)</td>
</tr>
</tbody>
</table>
features. What is more, it calculates the stomatal conductance of vegetation at three different canopy heights and adds them using Gaussian weights to obtain one bulk value representing the whole canopy. The new method accounts for secondary and tertiary diffuse sources, which were previously not considered in DALES, and includes scattering and reflection radiation losses. Furthermore, it accounts for the fact that due to the spherical distribution inside the canopy not all the sunlit leaves are perpendicular to the sun beam.

Table 4.1 shows the values obtained by the one-leaf A-gs method (1LEAF) and the new method presented for a total Photosynthetical Active Radiation at the top of the canopy $\text{PAR}^{\text{ToC}} = 300 \text{ W m}^{-2}$. For the new method, however, radiation has been distributed in different ways between direct and diffuse components to assess the sensitivity of the system to the partitioning between direct and diffuse $\text{PAR}$. The case DIR represents an ideal clear sky day with neither aerosols nor clouds in the atmosphere and where no diffuse radiation is present. The case DIRDIF imitates a realistic sunny day accounting for the diffuse radiation originated by aerosols or very thin clouds, as obtained from the delta-Eddington method. The cases DIFDIR and DIF represent a cloudy situation, although the absolute values of both $\text{PAR}$ components are significantly higher than typical values. They have been kept to be consistent in the total amount of $\text{PAR}$ reaching the canopy. The table shows that values of $A_n$ and $g_c$ increase for increasing ratio of diffuse light. This means that diffuse radiation is more efficiently absorbed by the canopy. If all the $\text{PAR}$ is set to be direct, obtained values of $A_n$ and $g_c$ are significantly smaller compared to the values given by 1LEAF. The two cases with more diffuse radiation (DIFDIR and DIF) give, however, the closest results to the previously existing DALES method (1LEAF). This similarity could be attributed to the fact that in the new scheme some factors increasing the final values of $A_n$ and $g_c$, such as secondary and tertiary diffuse radiation, are counterbalanced by other factors such as the leaf orientation and the scattered and reflected light. However, for cases with very small or no direct radiation at the top of the canopy, the secondary and tertiary diffuse radiation are almost negligible. Yet the values for 1LEAF and new scheme are almost identical. Thus, we can discard the balancing between additional diffuse radiation sources and effects accounting for radiation loss as the reason for this similarity. The difference between the most relevant extinction coefficients ($K_x = 0.7$ for the current method, $k_{df} = 0.71$ in the new method for this case) is very small too. Therefore, we can state with certain confidence that the scheme one-leaf A-gs was accounting radiation as almost pure diffuse radiation (clearly seen in the extinction coefficient $K_x$), in contrast to what was thought before: that this scheme was only considering direct radiation (Sikma, 2014; Vilà-Guerau de Arellano et al., 2014). Since diffuse radiation is known to penetrate more efficiently in the canopy, the 1LEAF experiment was showing a more active vegetation. This finding agrees with Dai et al. (2004), who affirmed that big-leaf models that treat a canopy as a single leaf tend to overestimate fluxes of CO2 and water vapor. With the new scheme, apart from a decreased performance of canopy, sensitivity to diffuse and direct contributions is incorporated.

Weighting all the additional features of the new model, the difference between extinction coefficients is the driving factor for the canopy performance. After averaging for 5 elevation angles, $k_{df} = 0.65$, a smaller number than $k_{df} = 0.71$, meaning that direct light would penetrate further in the canopy and, thus, less of it would be absorbed on its way. There is a more intuitive explanation for higher efficiency of diffuse radiation: at single leaf level, more radiation leads in general to more photosyntheses. However, as radiation increases, the increase in photosynthesis becomes less significant and reaches a saturation value dependent on the plant type. For c3 plants, the ones used in our model, saturation starts at $\text{PAR} = 200 - 250 \text{ W m}^{-2}$, with an asymptotic value of around $A_n = 1 \text{ mg m}^{-2}\text{s}^{-1}$. This feature is clearly shown by Vilà-Guerau de
**4.1.2 LAI dependence**

The dependence of canopy photosynthesis on LAI is multiple. As for shaded leaves, LAI directly affects its behavior at leaf level through Eq. (3.24). Similarly, performance of sunlit leaves at leaf
Figure 4.2: CO₂ stomatal conductance at canopy level $g_{c,can}^c$ as function of the Leaf Area Index for a situation with $PAR_{ToC}^{T=250} = 250 \text{ W m}^{-2}$ and $PAR_{ToC}^{T=250} = 50 \text{ W m}^{-2}$ and elevation and solar angle $\beta = \frac{\pi}{2}$. Light and dark blue dots indicate the contribution of sunlit and shaded leaves, respectively, to the total quantities given in black.

level depends on LAI through Eq. (3.25). This equations however do not show a clear tendency of photosynthesis to increase or decrease with LAI due to the interdependencies hidden in those expressions. Not to mention the fact that LAI affects the amount of shaded and sunlit leaves in the canopy, as seen in Eqs (3.36) and (3.37). The LAI factor is present for the last time in the second Gaussian, in order to convert the values from per leaf area to per ground area. Since it is not straightforward the overall effect of LAI on canopy photosynthesis, some cases have been simulated to test the response of the model to changes in canopy LAI.

Figure 4.2 shows the response of the canopy to changes in LAI. Three regions have been defined. The region (I), where an increase in LAI leads to an overall increment in stomatal conductance driven by the sunlit leaves; region (II), identified by a change of both sunlit and shaded contribution for growing LAI; and region (III), where the total increase in $g_c$ is mostly due to the contribution of shaded leaves. In regime (I), shaded leaves have no or very small contribution, of less than 15% to final $g_c$ values. This is because there is little diffuse light coming from the sky, and almost no diffuse radiation created in the canopy (see Fig. 3.4a). Thus, shaded leaves, only absorbing diffuse PAR, receive very little light. The rate in stomatal conductance increase is however reduced when we shift to higher values for the LAI at regime (II). An increase in LAI has one main consequences: first, for a higher LAI there will be more leaves and, therefore, the total stomatal conductance and photosynthesis rate per layer should increase provided all the leaves get enough radiation. This is what is observed for regime (I) and (II), since the contribution of sunlit leaves to total $A_{c,can}^c$ rises. In regime (II), however, contribution of shaded leaves to $g_c$ lies between 15% and 30% and can not be neglected any more. The reason is
that, as LAI grows, more leaves will be in the shade, and will absorb any diffuse radiation coming from above the canopy or scattered from sunlit leaves. What is more, as LAI grows (regime (III)) \( g_c \) reaches a saturation level for the sunlit leaves contribution. This can be attributed to the fact that beyond a certain threshold, probably dependent on the amount of radiation reaching the top of the canopy \( PAR^{ToC}_{dr} \) and \( PAR^{ToC}_{df} \), an increase on leaf density or LAI does not imply more photosynthesis within the sunlit canopy since almost all the direct radiation available is already absorbed by present leaves. Furthermore, all sunlit leaves will be saturated, so they will not absorb any additional direct or diffuse light. However, we still observe an increase in \( g_c \) by shaded leaves: as more radiation penetrates the canopy, more of it will be scattered and converted to diffuse. As diffuse light is generally of smaller magnitude compared to direct and it travels in all directions, there will still be a constant increase in stomatal conductance of shaded leaves, provided the sunlit ones are already saturated. There are two reasons for the steady increase of shaded contribution in regime (III): firstly, the larger marginal increase in photosynthesis for lower radiation (see Fig 11.2 in Vilà-Guerau de Arellano et al. (2015)), applicable at the lowest levels of the canopy. Secondly, a rise in LAI at regime (III) will imply not more sunlit leaves but more shaded leaves, increasing therefore the number of shaded and non-saturated leaves able to absorb diffuse radiation. In regime (III), contribution of shaded leaves climbs to 35%. Summarizing, we can characterize Figure 4.2 as the addition of two contributions: An initially quickly growing and later plateauing contribution of sunlit canopy, and a linearly increasing contribution of shaded canopy.

Figure 4.3: Temporal evolution of domain averaged diffuse radiation share over total radiation reaching the surface.
4.2 Surface partitioning

This section treats in depth the results of DALES simulations when the proposed delta-Eddington and canopy radiative transfer model are used. Thus, it is important to recall Fig. 2.1 and Table 2.1, where we defined the 6 experiments (DIF, NODIF, TOT, DIF5, NODIF5, TOT5) analyzed in this section.

In comparing the domain average total shortwave downwards radiation we find maximum differences of around 7% in the afternoon (not shown) for the NODIF cases where diffuse radiation from clouds is neglected. No significant differences in upwards shortwave radiation are found. Similarly, there are not important variations for downwards longwave radiation. Discrepancies of around 4% for upwards longwave radiation are observed in experiments with the single leaf canopy scheme (TOT and TOT5) due to the colder surface temperature being related to photosynthesis processes. These suggests the canopy in TOT experiments being more photosynthetically active, as it was already observed in Section 4.1.1 for situations with a larger contribution of direct radiation.

Figure 4.3 quantifies the amount and time of appearance of diffuse radiation in the domain, as well as its increase over time due to the onset of clouds at 13 LT. Maximum values are around 7% and there are no significant differences between the 4 simulations that account for diffuse radiation. An increase on LAI shows no relevant changes along the studied time.
Diffuse radiation has however a large impact on the surface partitioning through differences in the canopy stomatal resistance. Figure 4.4a shows important variations on vegetation resistance $r_{veg} = \frac{1}{T_{veg}}$ between cases with and without diffuse radiation (green lines), showing an increase as high as 40% in the afternoon for NODIF. Note that the lines in this figure do not give absolute values, but the ratios between NODIF and DIF experiments (green line), and between TOT and DIF experiments (red line). The differences in $r_{veg}$ are, however, reduced for the canopy net assimilation rates $A_n$ (Fig. 4.4b) due to additional factors contributing to $A_n$ (Equation (3.40)).

Different behavior is observed with the single leaf A-gs scheme (TOT and TOT5). As it was anticipated from the analysis in Section 4.1.2, this approach gives lower resistances and higher net assimilation rates as expected from Table (4.1), with shifts of between 30 – 40% for both $g_c$ and $A_n$. As suggested by Van Heerwaarden et al. (2009), the surface resistance plays an important role in regulating the surface fluxes. In contrast to the experiments without diffuse radiation (NODIF and NODIF5) where changes in evaporative fraction (defined as $EF = \frac{LE}{LE + SH}$) do not reach 5%, we now find larger differences for the TOT and TOT5 compared to the reference runs with raises of around 15% for most of the day (Fig. 4.4c). Although not shown, the ground heat flux $G$ barely changes between experiments, ranging between 10% and 13% of total surface fluxes over the simulated time. The larger difference for TOT experiments in EF is due to the lower values for vegetation resistance $r_{veg}$, since the contribution of vegetation to latent heat flux $LE_{veg}$ is calculated by:

$$LE_{veg} = \frac{\rho L_v}{r_a + r_{veg}} (q_{sat}(T_s) - \langle q \rangle)$$

where $q_{sat}(T_s)$ is the saturated specific humidity in the canopy, $\langle q \rangle$ the subcloud layer specific humidity, $\rho$ the air density and $L_v$ the latent heat for evaporation. $r_a$ represents the aerodynamic resistance and its values range between 60 – 65 s m$^{-1}$ during the time of interest. Figure 4.4 confirms, therefore, the fact that experiments using the single leaf A-gs for as canopy scheme (TOT and TOT5) have higher evapotranspiration rates than a more sophisticated 2-leaf canopy scheme (used in DIF and NODIF), as it was also found in the sensitivity analysis in Section 4.1.1. This may explain the lower values on upwards longwave radiation found previously for TOT experiments.

An increase on LAI has a different impact depending on the situation, as seen in Figure 4.4. In the cases without diffuse radiation LAI does not affect much the response of the surface, apart from smaller $r_{veg}$ and weaker variations due to clouds, although still reaching values around 20% higher than the reference DIF5. This means that as LAI grows, the importance of the diffuse radiation coming from the clouds decreases. The explanation is the following: at LAI=2, the profile of diffuse radiation inside the canopy is nearly constant, because the extinction rate of diffuse PAR is similar to the creation rate of secondary and tertiary diffuse in our model. This spreads diffuse light quite homogeneously and efficiently within the canopy (see Fig. 3.4). For LAI=5, diffuse PAR is extinguished much faster, there is almost no tertiary diffuse because almost no light reaches the ground, and generation of secondary diffuse is too weak to compensate the strong extinction. Thus, most of the diffuse is located at the top part of the canopy, where leaves already receive some direct PAR and may saturate. The diffuse PAR profile has large values at the top, but very low at the low canopy, making this distribution of PAR inefficient. Therefore, having diffuse radiation coming from clouds is less relevant for higher LAI, due to the strong extinction and in-homogeneous spread of the light within the canopy.
For the experiments accounting for a single PAR and the one-leaf A-gs scheme in the canopy (TOT), an increase in LAI leads to a small rise in photosynthetic activity and, accordingly, a decrease in $r_{veg}$ that yields an increase in evaporative fraction compared to DIF5 (set as reference), where diffuse radiation was explicitly considered both in the clouds and in canopy. For the TOT and TOT5 experiments no in-canopy radiation profiles are calculated. Therefore, more leaves will lead to more photosynthetic activity only limited by the saturation of leaves presented by Jacobs (1994).

4.3 Boundary layer dynamics

A more sensitive analysis in our research, considering diffuse radiation explicitly, allows us to deepen the effects of cloud shading on boundary-layer dynamics already investigated by Horn (2014); Sikma (2014). Vegetation responses to the different direct and diffuse partitioning lead to modifications in the distribution of the available radiation on sensible and latent heat flux (Figure 4.4c). The different behavior of vegetation and surface shown in Figure 4.4 impacts the evolution of the state and turbulent variables and boundary-layer growth. As metrics of these modifications, we show the evolution of turbulent kinetic energy (TKE) and boundary-layer height in Figure 4.5. There, the boundary-layer height is calculated as the height at which the gradient of the virtual potential temperature vertical profile reaches 50% of its maximum value (Ouwersloot et al., 2011; Sullivan et al., 1998).
Starting at 13LT, TKE is reduced in simulations without diffuse radiation from clouds (NODIF and NODIF5) up to 12% compared to DIF. This is because the energy associated to the diffuse radiation is not considered, creating weaker turbulences at the surface. The reduction in TKE due to less energy reaching the surface because of clouds was also found by Horn et al. (Submitted). Less available energy will very likely decrease the vertical velocity and buoyancy of the updrafts. This yields a shallower boundary layer when compared to experiments with and without diffuse radiation from clouds DIF and NODIF (Figure 4.4c). More precisely, a linear relation is found for this case between incoming shortwave radiation (decrease of 7%) and boundary-layer height (decrease of $\approx 8\%$). An increase in LAI leads in general to changes in the same order of magnitude: larger LAI implies larger stomatal conductance in the canopy (Fig. 4.2) and more latent heat flux (Eq. (4.1)). Thus, given the same amount of energy reaching the surface, sensible heat will decrease, reducing the buoyancy of the boundary layer and decreasing the average TKE and the boundary-layer height.

In Figure 4.5a we observe that for both LAI= 2 and LAI= 5, experiments using the single leaf A-gs (TOT and TOT5) lower the available average TKE around 12%. Similarly, this canopy setting delays and hampers the growth of boundary layer from the beginning, regardless of the presence of clouds, by around 6% (Fig. 4.5b). This is explained, once again, by the fact that an increase in evaporative flux and thus, latent heat, as observed in Figure 4.4 for TOT and TOT5, implies necessarily a reduction of the sensible heat flux SH provided that the same amount of energy reaches the surface. Less sensible heat leads to less buoyant updrafts, decreasing the entrainment rate at the top of the boundary layer and, therefore, hindering the boundary-layer growth, as it was also found by Chlond et al. (2014) and Vilà-Guerau de Arellano et al. (2014). Moreover, the appearance of clouds in all simulations decelerates the boundary-layer growth because clouds are known to be responsible for cloud venting, transporting moisture and momentum from the boundary layer to the free troposphere (Cotton et al., 1995; Neggers et al., 2006; Van Stratum et al., 2014). This findings are an extension of the research by Horn (2014), who found that the presence of clouds affects dramatically the boundary-layer growth, while the reduction of surface fluxes by cloud shading has a much smaller impact.

From Figure 4.5 we expect higher LAI, as well as the single leaf representation of A-gs canopy model (due to higher photosynthesis rates (Fig. 4.4)), to reduce the temperature in the subcloud layer, while increasing moisture due to a more active vegetation. Similarly, we would expect the lack of diffuse radiation in NODIF experiments to reduce the subcloud layer temperature.

### 4.4 Cloud properties

Cloud properties are largely dependent on surface flux ratios and magnitudes. Cloud base, similarly to boundary-layer height, increases if SH is higher (and LE lower), since more powerful but drier thermals appear and they reach higher and colder levels in the atmosphere. Larger LE leads to less, weaker but more moist updrafts, creating a lower cloud base (Vilà-Guerau de Arellano et al., 2014; Golaz et al., 2001; Lewellen et al., 1996). Thus, the ratio between SH and LE is a sensitive factor for cloud characteristics, and is not always easy to predict the impact of ratio variations, especially when it comes to cloud cover. Figure 4.6 shows the evolution of the cloud cover and thickness. Our findings, summarized in Table 4.2 quantify that the omission of
diffuse radiation leads to a 20 – 25% reduction of cloud cover regardless of the canopy LAI for the time of more intense cloud activity, that is, from 15:00 to 17:00 local time. This difference stresses the non-linearity of the process, provided that diffuse radiation never reached more than 7% of total radiation in the domain (Figure 4.3). Figure 4.6b shows the cloud thickness, calculated as the difference between the base and domain averaged top of the clouds. The larger cloud thickness values for experiments DIF can be explained by the fact that the extra energy coming from diffuse radiation heats up the surface. This raises SH and strengthens the updrafts, increasing the thickness that the clouds rooted in the surface updrafts can reach. Less energy reaching the surface in NODIF experiments (due to lack of diffuse light from clouds) makes updrafts less common and weaker, and clouds to be thinner and have less water content (Table 4.2). Liquid water path, shown in Table 4.2, shows similar behavior to cloud cover. The reason is that the liquid water path has been averaged over the whole domain, without removing the

Table 4.2: Domain averaged values of variables displayed in Figure 4.6 and Liquid Water Path averaged between 15:00 ad 17:00 LT. The table includes the ± standard deviation during the same time window.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Cloud cover</th>
<th>Cloud thickness (m)</th>
<th>LWP (Kg m⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIF</td>
<td>0.18 ± 0.01</td>
<td>1934 ± 300</td>
<td>0.19 ± 0.04</td>
</tr>
<tr>
<td>TOT</td>
<td>0.18 ± 0.01</td>
<td>1920 ± 250</td>
<td>0.19 ± 0.05</td>
</tr>
<tr>
<td>NODIF</td>
<td>0.14 ± 0.02</td>
<td>1871 ± 290</td>
<td>0.13 ± 0.04</td>
</tr>
<tr>
<td>DIF5</td>
<td>0.18 ± 0.01</td>
<td>1841 ± 350</td>
<td>0.19 ± 0.04</td>
</tr>
<tr>
<td>TOT5</td>
<td>0.17 ± 0.02</td>
<td>1837 ± 330</td>
<td>0.17 ± 0.05</td>
</tr>
<tr>
<td>NODIF5</td>
<td>0.13 ± 0.01</td>
<td>1739 ± 360</td>
<td>0.12 ± 0.03</td>
</tr>
</tbody>
</table>
points where no clouds were present. Thus, the calculated liquid water path is highly dependent on the amounts of clouds in the domain, explaining the similar behavior to the cloud cover. We can therefore affirm that the role of diffuse radiation in the boundary layer and available energy undoubtedly affects the characteristics of boundary-layer clouds, that are subject of study in this thesis. Therefore, the existence of links between surface, related fluxes and clouds stated in the literature is reinforced (Freedman et al., 2001; Lohou and Patton, 2014; Vilà-Guerau de Arellano et al., 2014).

The higher evaporative fraction in experiments with a single-leaf A-gs canopy scheme (TOT and TOT5) reduces the cloud cover around 5%. This is an indication that the SH and LE partitioning is affected by the diffuse radiation, and the subsequent impact on the cloud cover of the boundary layer. More precisely, LE is larger for TOT experiments (Figure 4.4c), reducing at the same time the energy available for SH and creating a more moist boundary layer but weaker updrafts. This leads to a lower cloud cover as it was also found by Chlond et al. (2014) and Vilà-Guerau de Arellano et al. (2014). A more detailed analysis on cloud characteristics will be done in Figure 4.8. An increase in LAI (dashed lines) does not change the sensitivity of cloud cover or thickness to diffuse radiation in a significant manner. Yet it does reduce the liquid water path of clouds, suggesting that larger LAI hampers the transport of water to the higher boundary layer through more moist but weaker updrafts.
Figure 4.8: Boundary-layer profiles of liquid water mixing ratio $q_l$ (left) and cloud cover (right). The values are result of averaging over the whole domain and over 2 hours between 15:00 and 17:00 LT.

### 4.5 Vertical profiles

In order to analyze how diffuse radiation modifies the vertical structure of the boundary layer, we select a time window presenting a well mixed boundary layer, large TKE and cloud activity, that is between 15:00 and 17:00 LT. For all profiles, the values at each height have been first spatially averaged for the whole domain. Afterwards, time averages of two hours have been taken, obtaining a representative profile for the whole domain during that time span. First profiles are given in Figure 4.7, showing the virtual potential temperature $\theta_v$, the total water mixing ratio $q_t$ and CO$_2$ concentration. In contrast to Figure 4.4a, where LAI was not influencing $r_{\text{veg}}$ significantly on the experiments without diffuse radiation from clouds (NODIF and NODIF5), we see variations of all bulk values due to a more active vegetation. Figure 4.7a confirms the higher boundary layer for DIF experiments. $q_t$ shows a smaller difference between subcloud layer and above values for DIF experiments. This suggests a more active transport of moisture from the boundary layer to above layers caused by the venting of a larger cloud cover in DIF experiments opposed to NODIF. In any case, all the differences due to diffuse radiation from clouds (between DIF and NODIF) in vertical profiles are very small compared to the variations shown for cloud characteristics in the previous section. This agrees with the hypotheses that diffuse light does not impact significantly on subcloud layer bulk values, but more on the top of the boundary layer and its clouds. To confirm this hypothesis, we show cloud liquid water mixing ratio $q_l$ and cloud cover profiles in Figure 4.8, as well as turbulent fluxes in Fig. 4.9. Green lines in both Figures 4.8a and 4.8b confirm that diffuse radiation should not be neglected, since
discrepancies on maximum values of \( q_l \) in the clouds are around 20%. Additionally, cloud cover shows larger values at same altitude for DIF experiments even after considering the difference of boundary-layer height.

Figure 4.7 shows, as it was suggested from the radiation analysis, that single leaf canopy scheme experiments (TOT and TOT5) giving larger stomatal conductance \( g_c \) (and higher photosynthesis rate \( A_n \) and lower \( r_{veg} \)) lead to a colder surface and, as consequence, colder bulk value \( \langle \theta_v \rangle \) for the boundary layer. The importance of the stomatal conductance \( g_c \) is further reinforced in Figures 4.7b and 4.7c, showing a subcloud layer with more moisture and lower CO\(_2\) concentration due to more photosynthesis in TOT experiments. This finding falls in line with the already shown Fig. 4.5b, where we expected colder and more moist boundary layer due to increased photosynthetic activity. Figure 4.8 shows that the dependence of cloud cover on canopy sensitivity (DIF and TOT experiments) is not large. Similar differences in the case for LAI=5 suggests that the impact of SH and LE partition on clouds does not change with LAI. This finding is reinforced by the research by Golaz et al. (2001), who also obtained small variations in maximum values of cloud cover in their LES study and affirmed that maximum values of cloud cover and water mixing ratio did not show significant changes under different soil-driven surface flux ratios. The main differences between TOT and DIF experiments in Fig. 4.8 are most likely due to surface-flux driven different boundary-layer heights.

Vertical fluxes of characteristic variables are given in Figure 4.9. The buoyancy flux \( \overline{w\theta_v} \)
shows the expected linear decrease until the inversion. The height at which this flux crosses the ordinate line fits quite well with the boundary-layer height shown in Fig. 4.5. The minimum $\overline{w\theta_v}$ values give an idea of the entrainment rates at the top of the boundary layer, of similar magnitude for the three experiments. Figure 4.9b shows results in agreement to what was expected from the profiles in Figure 4.7. There, lower variations of $q_l$ for DIF experiments suggested higher transport from the boundary layer upwards. In fact, this is what is observed in Figure 4.9b. This higher transport compared to the experiment without diffuse radiation from clouds (NODIF) matches with the larger cloud cover found for the experiment with diffuse radiation (DIF). Related to the cloud cover, Figure 4.9c clearly shows a higher maximum for DIF on upwards transport of CO$_2$ at around 1800 meters. The higher values compared to NODIF are explained by the larger (and thicker) cloud cover venting more CO$_2$ to higher altitudes. The positive flux associated to cloud venting is not found on DIF experiment when LAI=5. This is a consequence of what is shown in Fig. 4.7c, where CO$_2$ concentration has the same value below and above the boundary-layer top. Thus, cloud venting, which acts as a CO$_2$ transporting pipe for equilibrating subcloud layer and upper troposphere CO$_2$ concentrations is not relevant for the situation. This can be seen as an extreme case where the cross of the vertical 0 line happens at infinite height due to the overwhelming contribution of vegetation to CO$_2$ concentration reduction.
Chapter 5

Discussion

Our findings provide a quantification of the influence of diffuse radiation on the coupling between shallow cumulus and vegetated surface. In other words, by comparing our experiments we can attribute the differences to the diffuse radiation originated by the presence of shallow cumulus. Without accounting for diffuse radiation coming from above the boundary-layer top or from aerosols, diffuse radiation does not reach more than 7% of total radiation at the surface in our case study with shallow cumulus (Figure 4.3). Nevertheless, the simulated impact of the diffusion from clouds in the boundary layer is well beyond this 7%, demonstrating the non-linear response of vegetation to (diffuse) radiation. As shown in Figure 4.4, for a typical grassland with LAI=2 diffuse radiation can decrease the domain averaged vegetation resistance as much as 40% at some moments. This change is buffered in canopies with a higher LAI=5, never surpassing a difference larger than 20%. The reason for the buffering for higher LAI canopies is a more homogeneous diffuse light profile within the canopy, and thus a larger photosynthetic efficiency, at lower LAI (3.4). However, for both LAI=2 and 5 the evaporative fraction is only increased by less than 5% due to the diffuse light, because of other factors apart from vegetation photosynthesis, such as soil latent heat flux or aerodynamic resistance, contributing to surface fluxes. An increment of around 2 – 3 % in evaporative fraction was found by Lohou and Patton (2014) when comparing cloudy and cloudless regions but considering only direct radiation. Thus, this suggests that the increase in radiation when accounting for diffuse radiation from clouds is approximately as important as the reduction of direct radiation due to shading when it comes to domain-averaged evaporative fraction values. The increment in plant response due to diffuse PAR holds consequences for the boundary-layer dynamics due to the feedbacks existing between the surface and the subcloud layer (Van Stratum et al., 2014; Van Heerwaarden et al., 2009). The subcloud layer is affected by both heat and moisture flux changes due to diffuse light, creating more energetic turbulent motions which contribute to develop a boundary layer 8% higher than without the diffuse radiation coming from the clouds. Similarly, TKE is increased by between 10% and 20% during the time of most cloud activity, numbers in the same order of the decrease in TKE showed by Horn et al. (Submitted) when reduction of direct light by clouds is considered. This suggests, once again, that the impact of diffuse radiation from clouds can be as relevant as the reduction of direct radiation due to clouds for the dynamics of the boundary layer. Meanwhile, LAI does not have a clear impact on the subcloud layer sensitivity to diffuse radiation. The apparently linear dependence due to the contribution of diffuse radiation in the subcloud layer is however
amplified when it comes to clouds. Diffuse radiation accounts for a cloud cover and Liquid Water Path increase of 25%, while a small increase of less than 5% happens in cloud thickness. An increment in LAI from 2 to 5 increases these differences by around 5% in absolute numbers. Vertical profiles of the state variables in the boundary layer show little variations with or without diffuse radiation, except for the transport of moisture, heat and CO$_2$ associated to cloud venting, because diffuse radiation increases the presence and activity of clouds. These results agree with the findings by Lohou and Patton (2014), who showed that the entrainment rate and buoyancy fluxes are unaffected by the cloud-induced surface heterogeneities. Summarizing, we can state that the diffuse radiation from clouds, representing a small amount of the total energy at the surface, has little impact on the sub-cloud layer, but a very significant contribution at the top of the boundary layer where the shallow cumulus appear thicker, more often and more active.

The differences between experiments using a single-leaf (TOT) or two leaf A-gs canopy scheme (DIF) give us useful information on the previous big-leaf canopy scheme performance compared to the developed two-leaf scheme, as well as the opportunity to confirm the impact of the surface energy partition between sensible and latent heat flux on the whole boundary layer. The higher estimation on photosynthesis by the one-leaf A-gs scheme gives a 12 – 15% larger evaporative fraction. From Figure 4.5 we learn that this higher ratio of latent heat reduces the turbulent activity in a similar proportion (12%), as well as the height of the boundary layer. This is in agreement with the decrease in TKE under larger contribution of latent heat flux reported by Golaz et al. (2001), and the delayed and more shallow boundary layer under higher latent heat flux found by Chlond et al. (2014) and Vilà-Guerau de Arellano et al. (2014). However, no or little differences are found on cloud properties, especially for LAI=2. Vertical profiles confirm the fact that the shift in surface energy fluxes is not large enough to impact cloud properties as significantly as it does with the variables of the subcloud layer. This agrees with the findings by Golaz et al. (2001), where maximum cloud cover or maximum water mixing ratio were unaffected by small ratio variations between sensible and latent heat. Nevertheless, this cannot be generalized for larger variations in surface flux ratios, since Chlond et al. (2014) and Vilà-Guerau de Arellano et al. (2014) reported differences for maximum liquid water mixing ratio under larger variations in surface flux partitioning. The change in surface fluxes does affect bulk values in the subcloud layer such as $q_t$ or CO$_2$ concentration, a feature also reported by Golaz et al. (2001) and Chlond et al. (2014) for water mixing ratio and potential temperature in their experiments. Thus, we can conclude that the one-leaf A-gs scheme has a tendency for lower vegetation resistance and therefore higher (lower) latent (sensible) heat flux, impacting the whole boundary layer although leaving the cloud properties practically unaffected.

Recalling our research questions proposed in Section 1 and based on our results, we are now in a position to answer them:

- The dynamic partitioning of direct and diffuse radiation by clouds affects the photosynthetic rate of vegetation and, thus, the energy and surface fluxes at the surface. If the contribution of diffuse radiation from shallow cumulus is considered, vegetation resistance is reduced as much as 40%, increasing around 3% the evaporative fraction. Similarly, there are variations below 10% in CO$_2$ fluxes at the surface.

- Diffuse radiation by clouds suggest a linear-like relation with the domain averaged bulk TKE and boundary-layer height, although more experiments are needed for a confirmation. If diffuse radiation from clouds is considered, both variables increase around 8% and 10% respectively due to a higher input of energy leading to larger eddies and stronger updrafts from the surface.
• The impact of diffuse radiation on cloud dynamics is much larger than the effects observed at the surface or at the subcloud layer. By considering a vegetation representation that accounts for diffuse radiation from clouds and the transferring inside the canopy enhances cloud cover around 25% during the afternoon, and the domain averaged liquid water path grows more than 30%. Cloud thickness, however, is barely affected, growing only 3% in the analyzed time window.

• The one-leaf A-gs scheme gives higher photosynthetic rates compared to a direct-diffuse light sensitive two leaf A-gs scheme. This higher plant activity increases evapotranspiration, decreasing the sensible heat flux and, consequently the boundary layer average TKE and boundary layer height by around 12%. These changes lead to a colder and more moist boundary layer, without affecting the characteristics of the cloud layer.

• Carrying out a sensitivity analysis on LAI, more concretely imposing a larger LAI and repeating the same numerical experiments, does not change the impact of diffuse radiation importantly. With small changes in evaporative fraction in the order of 2%, the only significant variation is an increase of 5% in the difference in cloud cover and LWP between the experiment with diffuse radiation and two-leaf canopy scheme (DIF5). In order to understand better the sensitivity of diffuse radiation from clouds to canopy LAI and its consequences for the whole boundary layer, more experiments are necessary, where a more broad LAI sensitivity analysis, ranging from LAI values of 0.5 (very thin and short grassland) to 7 (high and compact forest) could be carried out in DALES.
Chapter 6

Conclusions and recommendations

The goal of this study was to investigate the role of diffuse radiation on the feedbacks existing between vegetation and shallow cumulus, and how this is affecting the surface and boundary-layer dynamics. For this purpose, we implemented a plan-parallel one dimensional radiative transfer model (delta-Eddington) to represent the scattering of light by water droplets in clouds, reducing the amount of direct radiation and converting part of it to diffuse radiation. A novel aspect of this study is the coupling of the atmospheric radiation transfer (delta-Eddington) to a radiative transfer representation within the canopy that accounts for both direct and diffuse radiation explicitly. The included two-leaf radiation transfer model inside the canopy, consisting of a sunlit and a shaded leave, was inspired in the model by Jacobs and De Bruin (1997). With this model, the canopy is sensitive to the diffuse or direct character of the light and we are able to quantify the amount of total photosynthesis occurring. In addition, reflection and scattering effects are considered, leading to the creation of diffuse light within the canopy. The behavior of this canopy radiation transfer scheme was partially validated with observations and another model approach discussed by Baldocchi et al. (1985). Main findings in a preliminary analysis suggested that diffuse radiation yields larger photosynthesis values than direct radiation at canopy level. The reason is that diffuse radiation spreads more homogeneously within the canopy, since both sunlit and shaded leaves absorb diffuse radiation, while direct radiation is only absorbed by sunlit leaves. After this off-line direct/diffuse ratio and a LAI sensitivity analysis for our radiative transfer model in the canopy, we implemented it in DALES and carried out the research for the boundary layer.

In order to specify our investigation, we formulated five research questions: what is the effect of direct and diffuse radiation partition at the surface? Does diffuse radiation from shallow cumulus affect the dynamics of the boundary layer? Are the dynamics of the boundary layer clouds affected by these changes in the boundary-layer dynamics? Are the differences between a two-leaf and one-leaf canopy schemes relevant for the evolution of the boundary layer and its clouds? Are any of these relations sensitive to the vegetation Leaf Area Index? To answer our research questions, we performed systematic experiments in DALES. DALES is a Large Eddy Simulation model that enables us to explicitly resolve the cloud dynamics and most of the
turbulences in the convective boundary layer. We used a simple microphysics scheme consisting on a relative humidity-based all or nothing situation for each gridbox. Furthermore, the land surface model coupled to it allowed us to understand the relations between the boundary layer and a vegetated surface. Our study was based on three experiments following one diurnal cycle with different approaches for diffuse radiation: simulating it explicitly within clouds and canopy; neglecting the diffuse radiation created at the clouds, but accounting for the one created inside the canopy; and simulating it as an aggregate radiation value together with direct radiation in clouds, and with the previously existing one-leaf canopy scheme developed by Ronda et al. (2001). Our results suggest that diffuse radiation does not vary significantly the domain average profiles of state variables within the boundary layer. However, diffuse radiation must be explicitly accounted for because of the enhancement on TKE and boundary-layer height growth it produces, and because of the non-linear relations linking diffuse radiation with cloud properties, which can lead to reductions of around 20% in cloud cover and average liquid water path if diffuse radiation is neglected. Moreover, differences on surface fluxes partition of 15% due to different in-canopy radiative transfer schemes are bound to affect the subcloud layer dynamics, without having such a big impact on the top of the boundary layer and its cloud properties.

Further improvements can be made on different aspects of this study. As for the canopy model, all other variables inside the canopy except radiation were assumed to be equal to its values at the surface. Thanks to this approach we were able to simulate more realistically the behavior of vegetation without increasing the computer costs tremendously. Accounting for the variation of other dynamic variables with height within the canopy such as leaf temperature or water vapor deficit may improve the representation of our canopy scheme. Examples of more developed in canopy schemes are the ones proposed by Patton et al. (2003) or Baldocchi and Wilson (2001). In fact, making other variables within the canopy sensitive to canopy depth may amplify the higher effectiveness of diffuse radiation over direct when it comes to canopy absorption. Moreover, only the radiative profiles within the canopy were validated due to lack of data. In Section 4.4 we mentioned the close relation between the liquid water path and the cloud cover, due to the methodology for calculation of liquid water path. In order to remove this dependence of LWP on cloud cover, we could define a "conditional LWP", similarly to what Horn et al. (Submitted) proposed for cloud optical thickness. This conditioned LWP would be calculated by averaging only over the columns containing clouds, instead of over the whole domain. In this way we could have a more clear indication on the water content of the individual clouds for each experiment, regardless of the cloud cover. Another improvement in the numerical experiments would be related to the position of the sun in the sky. The intensity of incoming radiation follows the daily pattern of the sun. However, the sun is located overhead for the whole simulation as far as the cloud shading is concerned, although in our canopy scheme we do account for the elevation angle of the sun, and the impact it has on the penetration of light in the canopy. However, a much more realistic and holistic approach would simulate the movement of the sun and the incidence of this on the elevation angle and the shade of clouds. At the beginning of the study, the fact that no aerosols were assumed in the whole atmosphere was mentioned. This is an obvious simplification, and accounting for them, or at least for their effect on diffuse radiation, would draw a more realistic picture of the processes really happening in the boundary layer and within the canopy. This could be done by adding a background diffuse radiation at the top of our domain in DALES, for example. For the same sake of completion, at least one experiment with a prescribed horizontal wind could be done, to see the sensitivity of the processes observed under more dynamic conditions. Finally, and in order to fully understand the impact of diffuse radiation, more numerical experiments could be done. One where the diffuse radiation both within clouds and canopy is neglected, and a last experiment with same settings
as our DIF experiment, but for transparent clouds. With the first of the experiments we would be able to understand the effect of diffuse radiation in the whole system (by comparing it to DIF experiment). With the second experiment, we could determine if the higher efficiency of diffuse radiation from clouds is enough to overcome the reduction of light by clouds. Because the aim was to characterize the main effects of diffuse radiation by clouds in the boundary layer, all the research in this thesis has mostly focused on the horizontally averaged effect of clouds in the domain. However, the high resolution of DALES also enables us to analyze the instantaneous local effects taking place. For example, the effect of cloud shading and diffuse radiation have at the vegetated surface, and its dependency on the optical thickness of the cloud. Thus, focusing on the area under the cloud would provide us with a better understanding on the local relations between clouds and vegetation.
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# Appendix A

## Initial conditions and prescribed variables

Table A.1: Initial atmospheric conditions for all LES experiments (Vilà-Guerau de Arellano et al., 2014).

<table>
<thead>
<tr>
<th>Height</th>
<th>Variable</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$z &lt; 114$ m</td>
<td>Potential temperature</td>
<td>284.00</td>
<td>K</td>
</tr>
<tr>
<td>$114$ m $&lt; z &lt; 138$ m</td>
<td></td>
<td>$284.00 + 4.166 \cdot 10^{-2} \cdot (z - 114)$</td>
<td></td>
</tr>
<tr>
<td>$138$ m $&lt; z &lt; 500$ m</td>
<td></td>
<td>$285.00 + 1 \cdot 10^{-3} \cdot (z - 138)$</td>
<td></td>
</tr>
<tr>
<td>$500$ m $&lt; z &lt; 4098$ m</td>
<td></td>
<td>$285.36 + 6 \cdot 10^{-3} \cdot (z - 500)$</td>
<td></td>
</tr>
<tr>
<td>$4098$ m $&lt; z &lt; 5466$ m</td>
<td></td>
<td>$292.56 + 6 \cdot 10^{-3} \cdot (z - 4098)$</td>
<td></td>
</tr>
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<td>$z &lt; 114$ m</td>
<td>Specific moisture</td>
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<td>g Kg$^{-1}$</td>
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<td>$4.3 - 8.33 \cdot 10^{-3} \cdot (z - 114)$</td>
<td></td>
</tr>
<tr>
<td>$138$ m $&lt; z &lt; 500$ m</td>
<td></td>
<td>$4.1 - 4 \cdot 10^{-3} \cdot (z - 138)$</td>
<td></td>
</tr>
<tr>
<td>$500$ m $&lt; z &lt; 4098$ m</td>
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<td>$3.942 - 1.2 \cdot 10^{-3} \cdot (z - 500)$</td>
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<td>$4098$ m $&lt; z &lt; 5466$ m</td>
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<td>0.015</td>
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Table A.2: Initial values for atmosphere, vegetation and soil (Vilà-Guerau de Arellano et al., 2014; Sikma, 2014).

<table>
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<tr>
<th>Description</th>
<th>Variable</th>
<th>Value</th>
<th>Units</th>
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<td><strong>Geography and time</strong></td>
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<td>51.97</td>
<td>deg</td>
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<tr>
<td>Latitude</td>
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<td>4.926244</td>
<td>deg</td>
</tr>
<tr>
<td>Longitude</td>
<td>DOY</td>
<td>268</td>
<td>-</td>
</tr>
<tr>
<td>Day of the year</td>
<td>xtime</td>
<td>7</td>
<td>UTC</td>
</tr>
<tr>
<td>Starting time</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Atmosphere</strong></td>
<td>$u_g,v_g$</td>
<td>0.01</td>
<td>m s$^{-1}$</td>
</tr>
<tr>
<td>Imposed geostrophic wind</td>
<td>$w_s$</td>
<td>0.0</td>
<td>m s$^{-1}$</td>
</tr>
<tr>
<td>Large scale subsidence velocity</td>
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<td></td>
<td></td>
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<tr>
<td><strong>Vegetation</strong></td>
<td>$c_{veg}$</td>
<td>0.9</td>
<td>-</td>
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<tr>
<td>Vegetation fraction</td>
<td>LAI</td>
<td>2.5</td>
<td>m$^2$ leaf m$^{-2}$ ground</td>
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<tr>
<td>Leaf Area Index</td>
<td>$\sigma$</td>
<td>0.2</td>
<td>-</td>
</tr>
<tr>
<td>Scattering factor</td>
<td>$r_{c,min}$</td>
<td>110</td>
<td>s m$^{-1}$</td>
</tr>
<tr>
<td>Minimum resistance transpiration</td>
<td>$r_{s,soil,min}$</td>
<td>50</td>
<td>s m$^{-1}$</td>
</tr>
<tr>
<td>Minimum resistance soil evaporation</td>
<td>$z_{0m}$</td>
<td>0.05</td>
<td>m</td>
</tr>
<tr>
<td>Roughness length for momentum</td>
<td>$z_{0h}$</td>
<td>0.01</td>
<td>m</td>
</tr>
<tr>
<td>Roughness length for heat and moisture</td>
<td>$a$</td>
<td>0.25</td>
<td>-</td>
</tr>
<tr>
<td>Surface albedo</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Equivalent water layer depth for wet vegetation</td>
<td>$W_l$</td>
<td>$1.4 \cdot 10^{-4}$</td>
<td>m</td>
</tr>
<tr>
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</tr>
<tr>
<td><strong>Soil</strong></td>
<td>$T_{soil1}$</td>
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<td>K</td>
</tr>
<tr>
<td>Soil layer temperature at 0.07 m</td>
<td>$T_{soil2}$</td>
<td>282.5</td>
<td>K</td>
</tr>
<tr>
<td>Soil layer temperature at 0.21 m</td>
<td>$T_{soil3}$</td>
<td>283.0</td>
<td>K</td>
</tr>
<tr>
<td>Soil layer temperature at 0.72 m</td>
<td>$T_{soil4}$</td>
<td>284.0</td>
<td>K</td>
</tr>
<tr>
<td>Soil layer temperature at 1.89 m</td>
<td>$T_{soil5}$</td>
<td>285.0</td>
<td>K</td>
</tr>
<tr>
<td>Deep soil layer temperature</td>
<td>$w_{sat}$</td>
<td>0.600</td>
<td>m$^3$ m$^{-3}$</td>
</tr>
<tr>
<td>Saturated volumetric water content</td>
<td>$w_{fc}$</td>
<td>0.491</td>
<td>m$^3$ m$^{-3}$</td>
</tr>
<tr>
<td>Volumetric water content field capacity</td>
<td>$w_{wilt}$</td>
<td>0.314</td>
<td>m$^3$ m$^{-3}$</td>
</tr>
<tr>
<td>Volumetric water content wilting capacity</td>
<td>$w_{soil1}$</td>
<td>0.385</td>
<td>m$^3$ m$^{-3}$</td>
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<tr>
<td>Volumetric water content soil layer 0.07 m</td>
<td>$w_{soil2}$</td>
<td>0.385</td>
<td>m$^3$ m$^{-3}$</td>
</tr>
<tr>
<td>Volumetric water content soil layer 0.21 m</td>
<td>$w_{soil3}$</td>
<td>0.385</td>
<td>m$^3$ m$^{-3}$</td>
</tr>
<tr>
<td>Volumetric water content soil layer 0.72 m</td>
<td>$w_{soil4}$</td>
<td>0.385</td>
<td>m$^3$ m$^{-3}$</td>
</tr>
<tr>
<td>Volumetric water content soil layer 1.89 m</td>
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<td></td>
<td></td>
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<tr>
<td>Root fraction 0.07 m</td>
<td>$r_{frac1}$</td>
<td>0.35</td>
<td>-</td>
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<tr>
<td>Clapp and Hornberer non-dimensional exponent</td>
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<tr>
<td>Hydraulic conductivity at saturation</td>
<td>$\gamma_{sat}$</td>
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<td>m s$^{-1}$</td>
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<tr>
<td>Matrix potential at saturation</td>
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<td>m</td>
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<tr>
<td>Skin layer thermal capacity</td>
<td>$C_{skin}$</td>
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<tr>
<td>Skin layer surface albedo</td>
<td>$\lambda$</td>
<td>3.0</td>
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</table>
Appendix B

Derivation of equation for radiation absorption by sunlit leaves

Equation (3.25) has been formulated in a way such that the total energy per area is conserved. We define $A$ as the total leaf area of a leaf perpendicular to the direct beam, having $m_{\text{leaf}}^2$ as units, where leaf means that the leaf is perpendicular to the direct beam. This beam has an average intensity given by $H_{\text{dir}}^{PP}$ as calculated in Eq. (3.23) and with units $W \text{ m}^{-2}$. Therefore, the total energy reaching the canopy at that area $A$ is given by:

$$E = A H_{\text{dir}}^{PP} \quad \text{(B.1)}$$

and $E$ has units of $W$. Since we have three different leaf orientations, as shown in Figure B.1, we need to know the amount of energy per perpendicular leaf area $[W \text{ m}^{-2}]$ that is absorbed by each orientation. However, it is clear that we cannot assume that this absorption is $H_{\text{dir}}^{PP}$ because in this case, since the total area of the three orientations ($A_1 + A_2 + A_3$) is bigger than the projections of these leaf orientations in the beam direction $A$, total energy would not be conserved. Therefore, we define a new normalized absorption $\tilde{H}$ with units $W \text{ m}^{-2}$, as follows:

$$\tilde{H} = \frac{H_{\text{dir}}^{PP}}{w_1 \sin \gamma_1 + w_2 \sin \gamma_2 + w_3 \sin \gamma_3} \quad \text{(B.2)}$$

The absorption at each orientation can be obtained with the help of Figure B.2. Looking at that Figure it is clear that the relation between $\tilde{H}$ and $H_i$ is given by:

$$H_i = \cos(\frac{\pi}{2} - \gamma_i) \tilde{H} = \sin(\gamma_i) \tilde{H} \quad \text{(B.3)}$$

Note that the units of $H_i$ are $W \text{ m}^{-2}$, meaning that $H_i$ is the projection of the beam on the direction perpendicular to a leaf orientated at an angle $\gamma_i$. The area at each orientation is defined as:

$$A_i = A w_i \quad \text{(B.4)}$$
Figure B.1: Sketch showing the orientation and area $A$ of a leaf perpendicular to the beam $H_{dr}^{PP}$, the leaf orientations and areas $A_1 = Aw_1$, $A_2 = Aw_2$ and $A_3 = Aw_3$ and the absorption $H_i$ for each leaf orientation. The angles $\gamma_1, \gamma_2$ and $\gamma_3$ give the leaf orientation with respect to the vertical axis.

Similarly to $H_i$, $A_i$ are given in $m_\text{leaf}^2$. Thus, we can understand the weighing factors $w_i$, that must be expressed in $m_\text{leaf}^2$, as projection factors of perpendicular-to-beam leaf areas on the direction of leaf angles $\gamma_i$.

In order to check that energy is conserved, we can calculate the total energy absorbed by the three orientations:

$$E^* = (A_1 H_1) + (A_2 H_2) + (A_3 H_3)$$
$$= (A w_1 \sin(\gamma_1) \tilde{H}) + (A w_2 \sin(\gamma_2) \tilde{H}) + (A w_3 \sin(\gamma_3) \tilde{H})$$
$$= A \tilde{H}(w_1 \sin \gamma_1 + w_2 \sin \gamma_2 + w_3 \sin \gamma_3) = A H_{dr}^{PP} = E$$  \hspace{1cm} (B.5)

Since the conservation of energy has been proved, we can conclude, reformulating Eq. (B.3) that the energy absorbed due to the direct beam reaching the leaves is given by:

$$H_i = \sin(\gamma_i) \frac{H_{dr}^{PP}}{w_1 \sin \gamma_1 + w_2 \sin \gamma_2 + w_3 \sin \gamma_3}$$  \hspace{1cm} (B.6)

Since the sunlit leaves will absorb the diffuse radiation as well, we can say that the total absorption of sunlit leaves will be that absorbed by shaded leaves plus the extra radiation absorbed
Figure B.2: Graph showing the angle relation between the normalized total absorption $\tilde{H}$ and the absorption $H_i$ for the leaf with inclination $\gamma_i$.

by each leaf orientation due to the beam reaching the leaves. Actually, this is the meaning of the expression given in Equation (3.25).

A similar approach to the one explained in this appendix can be found in Monson and Baldocchi (2014).