

Potential Implications of Lichen Cover for the Surface Energy Balance

*Implementing Lichen as a new Plant Functional Type
in the Community Land Model (CLM4.5)*

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Potential Implications of Lichen Cover for the Surface Energy Balance: Implementing Lichen as a new Plant Functional Type in the Community Land Model (CLM4.5)

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Abstract

We know that lichen cover in polar and high altitude regions may change due to grazing or climate change. Some previous studies have found that removal of lichen reduces the albedo and potentially changes the temperature, while others have focused on lichen's evapotranspiration. The purpose of this thesis is to quantify the importance of lichens for the entire surface energy balance as a whole, and the potential effects this may have on the temperature. This is investigated by implementing lichen as a new plant functional type (PFT) in the community land model (CLM4.5), and comparing the surface energy balance for lichen with other PFTs that may replace lichen. Comparisons are made between both idealised single column cases and for a larger grid in Finnmark with estimated lichen heath amounts from distribution modelling. Validation of the choice of parameter values for the lichen implementation is initiated by measuring the maximum amount of water in lichen and the rate of drying, but more validation is needed.

The results show that the properties that separate lichen from other vegetation, especially the albedo and evapotranspiration, give rise to surface energy fluxes that differ from other PFTs. The changes in the surface energy fluxes also influence the temperature. Lichen cover has a higher albedo than most other PFTs, which works to decrease the skin temperature. At the same time, the latent heat flux for lichen is very variable due high water holding capacity and lack of a root system. On average the latent heat flux is small for lichen, which works to increase the temperature. Because the simulations are performed offline, the surface energy fluxes' full potential for influencing the air temperature is not reached. However, the results suggest that lichen potentially can be important for the surface energy balance and local climate when studying the effects of vegetation changes in polar regions.

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Chapter 1

Introduction

The surface temperature, and in extension the climate, depends on the balance between incoming and outgoing energy at the surface. The ground receives energy from solar shortwave radiation and longwave radiation from the atmosphere. Some of the incoming solar radiation is reflected by the surface and the ratio of reflected to incoming solar radiation is defined as the albedo. The incoming energy must be balanced by outgoing energy from longwave thermal radiation from the Earth, sensible heat, latent heat and ground heat.

Vegetation can affect this balance in several ways. Albedo is one example, as vegetation differs in colour and amount of leaves. Other examples are emissivity, roughness, thermal conductance and the water storage capacity. All of these can directly influence the fluxes in the energy balance. And if one of the fluxes in the surface energy balance is changed, then this will lead to other changes because the system must be in balance. The vegetation cover therefore has a very important influence on the energy balance.

About 8% of the world's land surface has lichens as its dominant species (Ahmadjian, 1995) and it is a prominent part of polar and mountain regions (Nash III, 2008). It may therefore be important to include lichen when simulating these types of ecosystems. Nonetheless, lichens are not represented in many land surface models (LSM), including the Community Land Model (CLM4.5).

Lichens have many of the same properties as mosses, and act as an insulating layer above the ground (Porada et al., 2016; Stoy et al., 2012). Although lichens in many ways resemble mosses, lichens are not plants. They are a symbiosis between fungi and algae and/or cyanobacteria. As such, they resemble plants in some regards but not in others, also when it comes to the energy balance. While mosses are more important for carbon storage, and therefore noteworthy

on longer time scales (Smith et al., 2015), are lichens often lighter in colour than other vegetation and hence more important for the albedo and the surface energy balance.

Previous studies have found that removal of lichen in Fennoscandia and Alaska have reduced the albedo of snow-free ground (e.g. Cohen et al., 2013; Stoy et al., 2012). This means that while the ground is snow free, more of the solar insolation will be absorbed if lichen cover is removed. Lichens also have a large water storage capacity compared to other vegetation, and changes in lichen cover will therefore affect the evaporation from the vegetation (Bello and Arama, 1989). Other physical features for lichen may also differ from other vegetation and hence change the energy balance if removed. Still, a more comprehensive overview of how lichens impact the full energy balance at the surface is needed.

One factor that influences the lichen cover is the climate. We know the climate is changing due to anthropogenic influence (IPCC, 2013). Globally, the Earth is warming, and the largest warming is happening in the Arctic, referred to as Arctic amplification (e.g. Serreze and Barry, 2011). One of the consequences of this warming is changes in vegetation, and Fraser et al. (2014) found that warming in the Arctic can give increased amounts of shrubs, likely at the expense of lichen cover.

Another key factor is animals, and reindeer are especially important for the lichen cover. A compelling example of this is found when looking at the difference between Finland and Norway. Finland has heavier grazing by reindeer than Norway, and this have resulted in less lichen cover (Stoy et al., 2012). Figure 1.1 shows a satellite image of the border between Norway and Finland and we clearly see that the Norwegian side is lighter than the Finnish side, which is due to more light coloured lichens. However, the Norwegian side was even lighter in colour a few decades ago, before a great increase in reindeer population size since the beginning of the 1980s led to a decrease in lichen cover (Johansen and Karlsen, 2005). Reindeer grazing is therefore important for the lichen cover both now and in the future.

The purpose of this thesis is first and foremost to determine how important it is to include lichens in a LSM like CLM4.5 when trying to understand the surface energy balance. Are lichens different enough from other vegetation to make a significant difference on the surface energy balance? And if yes, what are these changes and how do they affect the temperature? The secondary purpose, given that lichen cover is important, is to quantify how changes in lichen cover in Finnmark may affect the surface energy balance and potentially the temperature. What consequences does a reduction in the lichen cover, due to e.g. grazing or



Figure 1.1: Google Maps satellite photo of the border between Norway (top) and Finland (bottom). The lighter colour on the Norwegian side is due to larger amounts of light coloured lichens. Reproduced from Google (2018).

climate change, have?

Lichens are present both as the dominating species, in lichen heath, and together with other vegetation, e.g. as the part of the forest floor. However, when lichens are present under other vegetation like trees and shrubs the properties of lichens will not be as important, and the properties of the taller vegetation will dominate. This is because the taller vegetation will receive most of the sunlight and have the dominant reflectance effect, and it is also the vegetation that will have the best access to available water and so on. In this study, the focus will thus be on lichen heath, as the effects of lichen amount changes under other vegetation will be difficult to include and probably be small.

To explore this problem, I have implemented lichen as a plant functional type (PFT) in CLM4.5 with focus on the biogeophysical properties. To answer the questions posed above, lichen is compared to other PFTs that are likely to replace lichen, and a regional run for Finnmark with estimated amounts of lichen heath is compared to runs where lichen is removed.

Chapter 2

Theory

2.1 The Energy Balance

The energy balance of the Earth can be divided into three levels as illustrated in figure 2.1: the top of the atmosphere (TOA), the surface and the atmosphere in between. At each level the amount of incoming and outgoing energy must be equal.

The focus of this thesis is the balance at the surface which can be written as

$$(1 - \alpha)S \downarrow + L_{atm} \downarrow - L \uparrow = H + \lambda E + G \quad (2.1)$$

where α is the surface albedo, $S \downarrow$ is the incoming solar radiation, $L_{atm} \downarrow$ is the incoming longwave radiation from the atmosphere, $L \uparrow$ is the thermal emissions from the surface, H is the sensible heat flux, λE is the latent heat flux and G is the heat flux into the ground. For the latent heat flux, λ is the latent heat of evaporation and E is the water vapour flux. The latent heat of evaporation is the amount of energy it takes to evaporate a substance, given in J/kg. For water it takes about $2.3 \cdot 10^6$ J/kg. When water vapour condensates, the same amount of energy is released.

In addition to dividing radiation into shortwave and longwave, the shortwave radiation is divided into direct and diffuse radiation. The direct radiation is the solar radiation that goes in a straight line from the sun to the surface. Diffuse radiation is the radiation that is scattered in the atmosphere before reaching the surface.

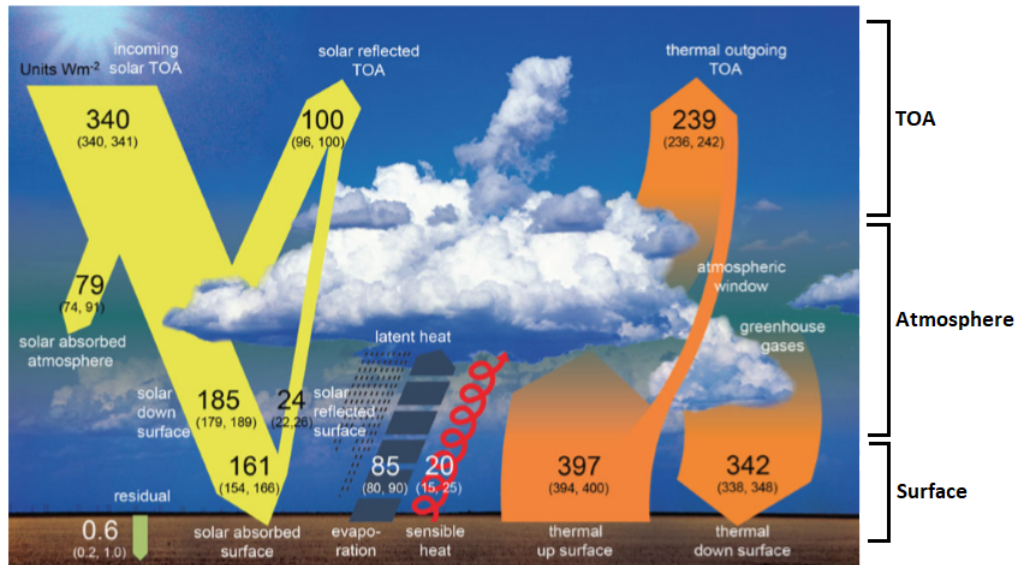


Figure 2.1: The global mean energy balance of the Earth, with best estimates of each component with uncertainties in W/m^2 . Modified from Wild et al. (2013).

2.1.1 Radiative Fluxes

The incoming shortwave radiation comes from the sun, which emits an approximately constant amount of energy at all times (neglecting the 11-year cycle, etc.). The amount of solar radiation reaching the Earth varies throughout the day due to the Earth's rotation, causing a daily cycle of incoming solar radiation. Also, the received amount of solar radiation depends on the latitude, with most being received at the equator and less at higher latitudes due to the spherical shape of the Earth. Additionally, the amount received depends on the distance to the sun. This varies through the year and also on longer scales of decades or centuries (e.g. Milankovich cycles), but the differences are small. In the atmosphere the radiation might be reflected or absorbed, and of the solar radiation reaching the Earth's surface a portion is reflected by the surface.

As mentioned, the albedo is defined as the ratio of reflected to incoming solar radiation. Another important property is the reflectance. This quantity is quite similar to the albedo but is the ratio of reflected radiation to incoming radiation for a given wavelength or frequency. Different types of lichen can have a wide variety of different colours, but many of the most common lichens, and the ones in focus here (see subsection 2.2.1), are light in colour compared to other vegetation. This would suggest a higher albedo than other vegetation. Additionally, the height of the vegetation is important for the albedo, since this will affect how

long it takes for the vegetation to be covered by snow, which typically has a considerably higher albedo than the surface below. Lichen is lower than most other vegetation and can potentially be covered faster by snow in the autumn and stay covered longer in the spring, resulting in a higher albedo during these transitions. However, the low, even vegetation cover that lichen provides also makes it easier for the snow to blow off at exposed sites.

Longwave radiation flux from the Earth varies with both surface temperature and emissivity ϵ as given by Stefan-Boltzmann's law:

$$L_{\uparrow} = \epsilon \sigma T_s^4 \quad (2.2)$$

where σ is the Stefan-Boltzmann constant and T_s is the surface temperature. The emissivity is defined as the ratio of emitted intensity to emitted intensity from a black body with the same temperature and tells us how effective a medium is at emitting energy as thermal radiation. The longwave radiation from the atmosphere similarly depends on the atmosphere's temperature and emissivity.

2.1.2 Turbulent Fluxes

The lowest part of the atmosphere, which is directly affected by the surface, is called the atmospheric boundary layer. Its thickness ranges from a few metres to a few kilometres depending on the local meteorology. It is within this layer that turbulence is generated and works to mix and redistribute heat, moisture and other atmospheric properties. Turbulence is an irregular fluid flow consisting of swirling motions called eddies. It can be caused by thermal convection due to differential heating or by forced convection due to friction and wind.

Forced convection occurs when horizontal wind moves over a surface and the roughness of the surface (e.g. due to vegetation or other obstacles) causes a surface friction working in the opposite direction of the wind. This friction slows the wind near the surface, and at some level above the true surface the wind velocity will be zero. This is called the virtual surface. Below the virtual surface turbulence is suppressed by the surface roughness elements.

If we extrapolate a logarithmic profile of the horizontal mean wind speed, the wind will equal zero at height $z = z_d + z_0$ where z_d is the displacement height, z_0 is the roughness length and the sum of the two is the virtual surface (Dingman, 1994). Figure 2.2 shows this wind velocity profile. This is, of course, a simplified model of the actual profile but still give us some intuition regarding z_d and z_0 . As

indicated in the figure, both roughness length and displacement height depend on the height of the vegetation (Dingman, 1994).

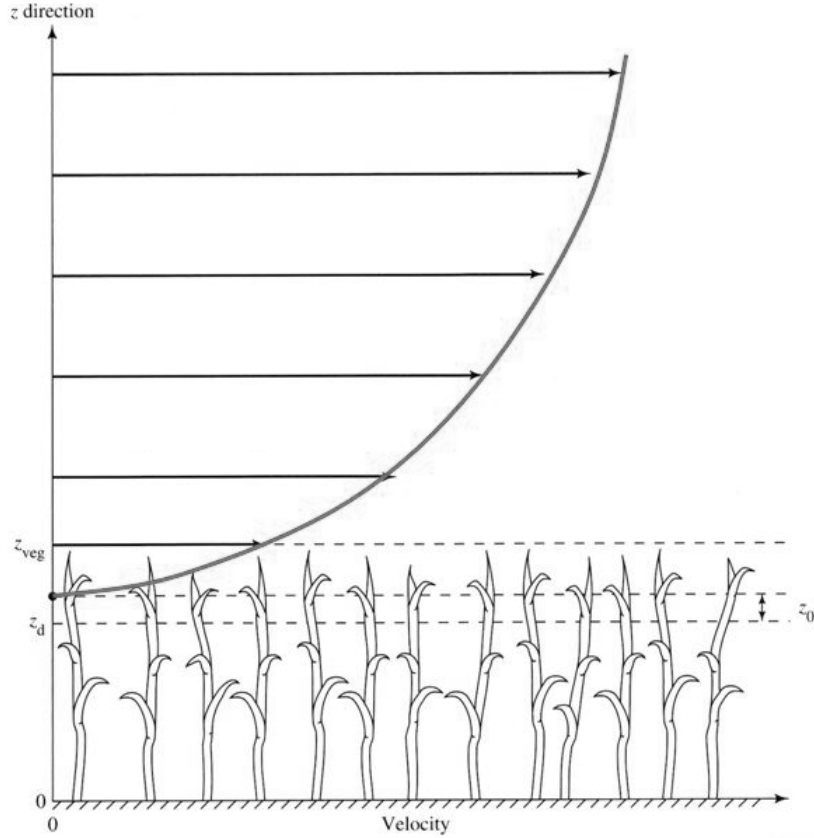


Figure 2.2: The vertical wind velocity profile over vegetation. The bold line follows a logarithmic profile and reaches zero at the virtual surface. Modified from Dingman (1994).

Sensible heat is thermal energy that results in a temperature change when transferred. When looking at the surface energy balance we are interested in the sensible heat flux between the surface and the air above it, and we define a positive sensible heat flux when heat is transferred upward. Sensible heat depends on the temperature gradient between the ground and higher up, and are driven by two processes: molecular conduction and turbulent convection (Wallace and Hobbs, 2006). Molecular conduction happens within the bottom few millimetres of the atmosphere due to a very large temperature gradient between the surface and the air above. Above these few millimetres molecular conduction is negligible and turbulent convection dominates.

Latent heat is thermal energy that is absorbed or released by a substance during a phase transition without changing the temperature. In the context of the surface energy balance, the latent heat flux is the heat flux between the surface and the atmosphere that is associated with evaporation or condensation of water vapour at the surface. For a positive upward latent heat flux from the surface, water vapour is transported upwards and is converted to sensible heat and/or potential energy when the water vapour condenses (Wallace and Hobbs, 2006). Just like sensible heat depends on the temperature gradient, latent heat depends on how the humidity changes with height. It is also similarly transported by turbulence and conduction.

At day, the sum of the radiative fluxes is typically negative as the incoming solar radiation is much larger than the outgoing longwave radiation. If there is water available, most of this energy goes into evaporation giving a large positive latent heat flux. Since the solar radiation heats the surface faster than the air above, the sensible heat will also be positive but typically small. The sensible heat can also be negative if hot, dry air comes in over a cool, moist surface. If the area is very dry, the sensible heat flux will be considerably larger than the latent heat flux. At night there is no incoming solar radiation and the radiative flux is therefore positive while the sensible and latent heat fluxes are negative.

2.1.3 Ground Heat Flux

Heat is transferred into the ground by conduction if there is a temperature difference between the surface and the subsurface. The first law of heat conduction (Fourier's law) in one dimension can be written as

$$G = -\lambda \frac{\partial T}{\partial z} \quad (2.3)$$

where G is the amount of heat conducted across a unit cross-sectional area given in W/m^2 , λ is thermal conductivity given in W/(m K) and $\frac{\partial T}{\partial z}$ is the gradient of the temperature with depth (K/m).

Assuming steady state heat conduction, this is the ground heat flux and is defined as positive into the ground. In addition to temperature, the insulating effect of the soil and the surface layer (contained in the thermal conductivity), including the vegetation, also influences the flux. The ground heat flux will typically be positive during the day and negative during the night.

2.2 Lichen

Lichens have a considerable variability in shape, colour and where they grow. However, the interactions between the fungi and the algae/cyanobacteria are similar in all lichens. The fungi are responsible for most of the body of the lichen, the *thallus*, and needs carbohydrates to grow and reproduce. Photosynthesis is the transformation of light energy into chemical energy and is performed by algae/cyanobacteria to produce the needed carbohydrates (Gasulla et al., 2012). Still, photosynthesis in lichen is small compared to vascular plants (Huemmrich et al., 2013).

Lichens do not possess roots but instead obtain water from the air through rain, dew, fog and high air humidity (Nash III, 2008). Transpiration is the process of water being transported through the plant from the roots and into the leaves where it evaporates and is realised into the air. Because lichens don't obtain water through their roots they cannot transpire like plants.

The growth of lichens is typically slow, but they are long-lived (Asplund and Wardle, 2017). They often dominate places that are too cold, dry or nutrient-poor for other vegetation, but occur as part of most terrestrial ecosystems, although mostly as a minor component (Asplund and Wardle, 2017).

2.2.1 Lichens in Finnmark

The most important lichen species in Finnmark are mostly from the *Cladonia* (cup lichen) genus. Important species are *C. stellaris*, *C. arbuscula* and *C. rangiferina*, all commonly known as reindeer lichens, and *Flavocetraria nivalis* (Tømmervik et al., 2014). Common for all of these lichen species are the light colour.

Johansen and Karlsen (2005) documented that lichen cover in Finnmark has greatly diminished since the beginning of the 1980, corresponding to a large growth in the reindeer population. They used spectral bands from satellite images to map the vegetation. One difficulty with this is that some vegetation types have very similar spectral information, making them difficult to separate. To minimise this problem digital elevation models, field inventory data, digital topographic maps and land cover layers of forests, mires, water, and open areas was used. However, the availability and quality of this information were varying.

The reindeer population increased from 90 000 animals in 1976 to 210 000 in

1988 (Johansen and Karlsen, 2005). Due to the reindeer herding in Finnmark we have three different grazing pastures. In winter the reindeer stay at the inner, continental parts of Finnmark, in summer they stay at the coast and in spring and autumn they migrate between the two. The lichen cover will therefore vary between these regions. This is in strong contrast to Finland where the reindeer graze in the same area all year. A fence at the boarder prevents mixing of Norwegian and Finnish reindeer and separates the much more heavily grazed Finnish side from the Norwegian side (Johansen and Karlsen, 2005) as seen in figure 1.1.

Figure 2.3 shows how intact lichen cover and grazing pressure have changed from 1973 to 2000 based on satellite data, and table 2.1 gives the percentages of lichen cover within the winter and migration pastures from Johansen and Karlsen (2005). Both the table and the figure show a clear trend towards less lichen cover.

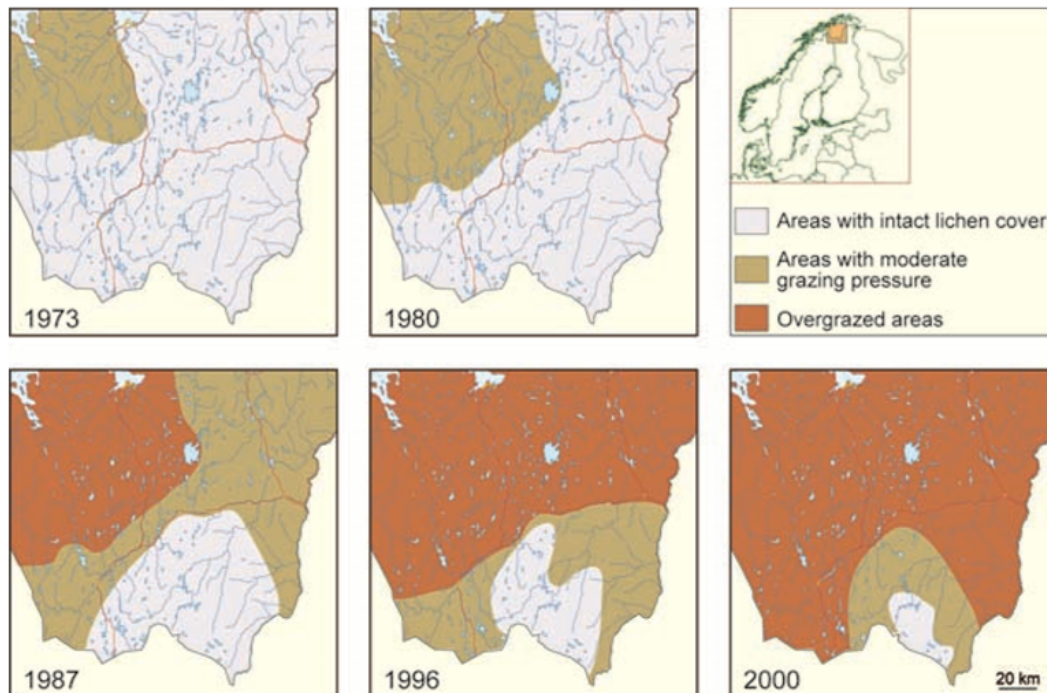


Figure 2.3: Distortion map summarising the decline in lichen cover on Finnmarksvidda, Northern Norway, for the period 1973-2000. Reprinted from Johansen and Karlsen (2005)

Table 2.1: Lichen cover within the winter and migration pastures in Finnmark between 1973 and 2000. The total area is 16,501.7 km². Summarised from Johansen and Karlsen (2005)

Year	km ²	%
1973	4576.0	27.7
1980	3736.5	22.6
1987	2053.3	12.4
1996	716.6	4.3
2000	412.6	2.5

2.2.2 Consequences of Reindeer Grazing

According to Lent and Klein (1988) can heavy grazing reduce or even completely remove both deciduous shrubs and preferred lichen species. The lichen cover can be removed in only a few years, while it takes decades for lichen to regrow (Klein, 1987; Olofsson, 2006). There are two main reasons why reindeer grazing can be so devastating for the lichen cover. Firstly, lichens are an important food source for reindeer, especially in winter (Lent and Klein, 1988). The other reason is that lichens are more sensitive to trampling than other vegetation (Cooper et al., 2001). Especially when the lichen is dry can the effect of trampling be substantial (Heggenes et al., 2017).

The effect of removal of shrubs is also important for the surface energy balance. te Beest et al. (2016) found that heavy grazing increased the summer albedo by decreasing the shrub height. However, they noted that the effect of decreases in lichen was not included and might affect the results. Cohen et al. (2013) found that grazing led to delayed snow melt due to reduced amounts of shrubs and therefore increased albedo. The effect of reduced shrubs is not included in this thesis but is still important to keep in mind when interpreting the results.

Stoy et al. (2012) found both the albedo and the night-time temperature to be significantly higher on the Norwegian side than on the Finnish side of the border fence, suggesting a small surface cooling from overgrazing. They explained the counter-intuitive result of both higher albedo and surface temperature for areas with more lichen as a result of lichen's weak conductance of heat in the subsurface.

Chapter 3

Models and Methods

3.1 CLM4.5

The Community Land Model (CLM) from the Community Earth System Model (CESM) was used to carry out this study. The model provides a systematic way of inspecting the surface fluxes. In CLM, all parts of the surface energy balance are calculated consistently, and the same situation can be simulated many times, e.g. with various vegetation, making it easy to compare. The model version used here is CLM4.5. For a full description, see Keith W. Oleson (2013), from which the content of the following description (including subsection 3.1.1 and 3.1.2) is based, unless otherwise noted.

CLM4.5 solves the surface energy and water balances based on the first principals of conservation of energy and mass. (It can also solve the carbon balance but that is not included in this thesis.) Additionally, it simulates physical, chemical and biological processes at the surface and in the soil, e.g. vegetation and snow cover.

The model is one-dimensional and can be run for the entire globe or a smaller region. The chosen area is divided into grid cells of a given resolution. The grid cells are divided into a number of land units which is the first of three subgrid levels. Each land unit can then be divided into a different number of soil and snow columns and these can consist of multiple plant functional types (PFTs). This is well illustrated in figure 3.1.

The land units are a rough classification and currently consist of glacier, lake, urban, vegetation and, if the crop model is active, crop. The columns are used to capture variability in soil and snow within a single land unit, although in CLM4.5

only the crop and the urban land unit has more than one column. The vegetated land unit can be divided into multiple PFTs, including bare ground, to capture the biogeophysical and biogeochemical differences between various vegetation. This unit only has one column so that the different PFTs must compete for water and nutrients.

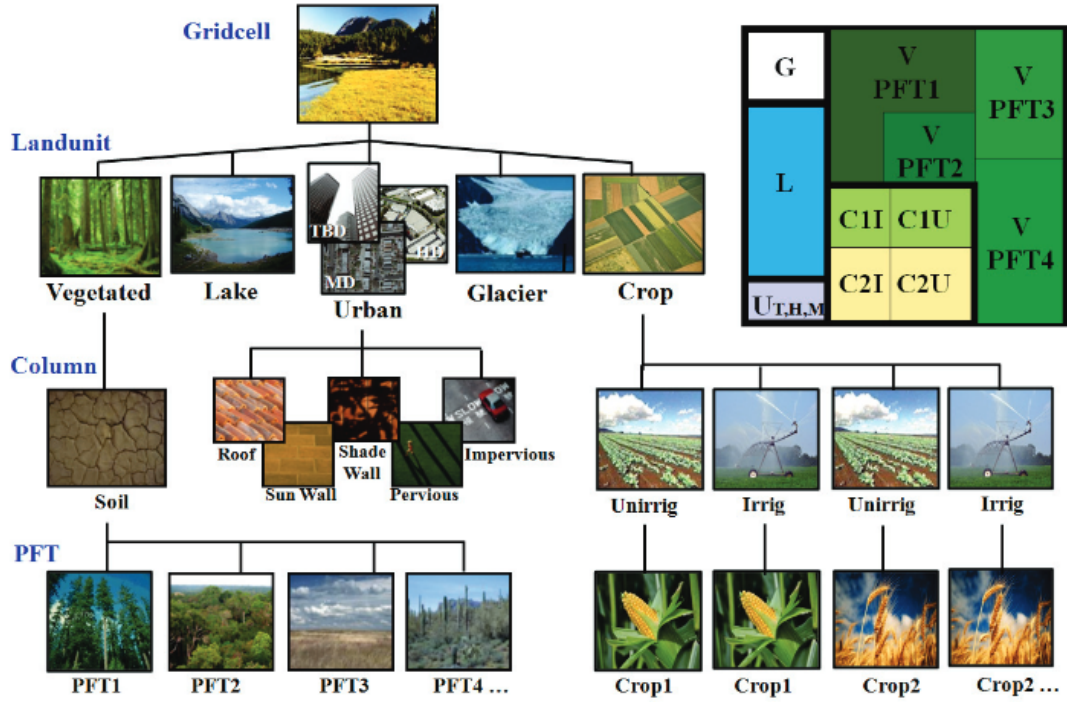


Figure 3.1: The CLM grid cell structure. Abbreviations: TBD – Tall Building District, HD – High Density, MD – Medium Density, G – Glacier, L – Lake, U – Urban, C – Crop, V – Vegetated, I – Irrigated, U – Unirrigated. Reprinted from Keith W. Oleson (2013)

Vegetation state variables (e.g. vegetation temperature and canopy water) and fluxes to and from the surface is defined at the PFT level. Variables calculated at the PFT level can be used at higher levels, generally by computing a weighted sum over all PFTs depending on the PFT area relative to all PFTs in the column. The state variables for water and energy, and fluxes of these, in the soil and snow, is defined in the column. Fluxes to and from the atmosphere are calculated at the grid level from the fluxes defined at the PFT level.

3.1.1 Plant Functional Types (PFTs)

In the vegetated land unit, which is the unit that is of most interest here, the column can consist of up to 16 PFTs, including bare ground. A list of all the PFTs is given in table 3.1.

Table 3.1: List over names and acronyms of the 15 PFTs (excluding bare ground).

Plant Functional Type	Acronym
Needleleaf evergreen tree - temperate	NET Temperate
Needleleaf evergreen tree - boreal	NET Boreal
Needleleaf deciduous tree - boreal	NDT Boreal
Broadleaf evergreen tree - tropical	BET Tropical
Broadleaf evergreen tree - temperate	BET Temperate
Broadleaf deciduous tree - tropical	BDT Tropical
Broadleaf deciduous tree - temperate	BDT Temperate
Broadleaf deciduous tree - boreal	BDT Boreal
Broadleaf evergreen shrub - temperate	BES Temperate
Broadleaf deciduous shrub - temperate	BDS Temperate
Broadleaf deciduous shrub - boreal	BDS Boreal
C ₃ arctic grass	-
C ₃ grass	-
C ₄ grass	-
Crop	-

As seen from table 3.1 there are trees, shrubs, grass and crop represented in CLM4.5. Trees are either broadleaf or needleleaf, while all shrubs have broadleaf. A plant's amount of leaves usually changes throughout the year depending on the season or the meteorological conditions. The timing of these changes and other biological events of the plant are called phenology. In CLM the PFTs are divided into three types depending on their phenology: evergreen, seasonal-deciduous and stress deciduous. The evergreen type have some fraction of leaf growth that consists through the year, while seasonal-deciduous is mainly controlled by temperature and day length and have a single growing season through the year. Stress-deciduous can potentially have several growing seasons through the year, controlled by temperature and soil moisture.

The PFTs are defined by a number of properties divided into three classes: morphological, photosynthetic and optical. Morphology includes roots, leaves, stems and aerodynamic parameters, and controls among other things the PFTs uptake of water. The photosynthetic parameters decide photosynthesis and transpiration. Lastly, the optical properties determine the reflection, absorption and

transmittance of solar radiation. Additionally, I have defined a fourth class, hydrology, which includes the parameters that affect the water amount in the PFTs. Unlike the first three classes, which are given in input files, these parameters are set directly in the source code and are the same for all PFTs.

There are three main sub-modes for CLM4,5 (Kluzek, 2013). The model can have prescribed phenology, meaning that the cyclic variables, e.g. height and the leaf and stem amounts, of each PFT is set, or it can have carbon and nitrogen cycle with single- or multi-layer. The three sub modes are listed under.

- **Satellite Phenology (SP)**
 - No carbon-nitrogen cycle in the model
 - Phenology of vegetation is prescribed
 - Vegetation cover is prescribed
- **Carbon-Nitrogen (CN)**
 - Have carbon-nitrogen cycle in the model
 - Single-layer carbon and nitrogen pools in the soil
 - Vegetation cover is prescribed
- **Biogeochemistry (BGC)**
 - Have carbon-nitrogen cycle in the model
 - Multi-layer carbon and nitrogen pools in the soil
 - Vegetation cover is prescribed

In addition, there are three modes that can be used together with these sub-modes: *Dynamic Vegetation (DV)* mode where the vegetation cover is dynamic can be used for CN and BGC, a crop model *CROP* that can be used with CN and BGC, and *Variable Infiltration Capacity (VIC) hydrology* which can be used with SP (Kluzek, 2013).

Carbon and nitrogen cycle were not part of the study, and the satellite phenology sub-mode was therefor used.

3.1.2 Energy Balance in CLM 4.5

To understand how lichens affect the energy balance, we must understand how the energy balance is represented in CLM4.5 and how the separate components of the balance are calculated. The energy balance in CLM4.5 is

$$S_g + S_v + L_{atm} \downarrow - L \uparrow = H_g + H_v + \lambda E_g + \lambda E_v + G \quad (3.1)$$

where S is the absorbed solar radiation by the ground (g) and the vegetation (v), $L_{atm} \downarrow$ is the downward atmospheric longwave radiation, $L \uparrow$ is the upward

longwave radiation from the vegetation and the ground, H is the sensible heat flux and λE is the latent heat flux for the ground (g) and the vegetation (v) and G is the ground heat flux. All terms are given in W/m^2 .

Radiative Fluxes in CLM4.5

How much of the solar radiation that is absorbed depends on the reflectance and transmittance of the PFT for vegetation. For the ground this depends on the optical parameters for soil, but also on how much vegetation that is blocking the ground.

The longwave radiation can be divided into longwave radiation from the atmosphere $L_{atm} \downarrow$ and emitted radiation from the Earth itself $L \uparrow$. The radiation from the atmosphere depends on the temperature of the atmosphere. As such, this quantity is calculated from the temperature, pressure and humidity from the atmospheric forcing data (Kluzek, 2013) and will be the same for all PFTs. However, it should be noted that the amount of absorbed longwave radiation, the absorptivity of the surface, varies between the vegetation and with the fractional snow cover. The longwave radiation emitted from the surface depends on the surface temperature and emissivity, which depends on the PFT, as seen in equation 2.2. In addition to the thermal emittance given by Stefan-Boltzmann's law, the outgoing radiation from the surface also has contributions from the reflected part of the incident longwave radiation.

For vegetation CLM4.5 calculates emissivity as

$$\epsilon_v = 1 - e^{-(LAI+SAI)/\bar{\mu}} \quad (3.2)$$

where LAI is the exposed leaf area index and SAI is the exposed stem area index defined as leaf and stem area per unit area at the ground (see section 4.1) and $\bar{\mu} = 1$ is the average inverse optical depth for longwave radiation. For snow-free soil $\epsilon_{soi} = 0.96$ and for snow $\epsilon_{sno} = 0.97$. The absorptivity is assumed to be equal to the emissivity.

Turbulent Fluxes in CLM4.5

The vegetation is assumed to not store any heat or water vapour. Therefore, when the surface is vegetated, sensible heat H and water vapour E are split into ground and vegetation fluxes, depending on the ground temperature T_g and the

vegetation temperature T_v respectively. The ground temperature is the temperature of the top soil layer and the vegetation temperature is the temperature of the vegetation.

Sensible heat flux from the vegetation is calculated as

$$H_v = -\rho_{atm} C_p \left[\frac{\theta_{atm} - T_v}{r_{ah}} + \frac{T_g - T_v}{r'_{ah}} \right] \frac{LAI + SAI}{\frac{r_b}{r_{ah}} + \frac{r_b}{r'_{ah}} + LAI + SAI} \quad (3.3)$$

where ρ_{atm} is the density of atmospheric air, C_p is the specific heat capacity of air, θ_{atm} is the atmospheric potential temperature, r_{ah} is the aerodynamic resistance to sensible heat transfer between the vegetation and the air, r'_{ah} is the aerodynamic resistance to sensible heat transfer between the ground and the vegetation and r_b is the leaf boundary layer resistance.

The water vapour flux from the vegetation is calculated as

$$E_v = -\rho_{atm} \left[\frac{q_{atm} - q_{sat}^{T_v}}{r_{aw}} + \frac{(q_g - q_{sat}^{T_v})\beta_{soi}}{(r'_{aw} + r_{litter})} \right] \frac{(LAI + SAI)r''}{\frac{r_b}{r_{aw}} + \frac{r_b\beta_{soi}}{(r'_{aw} + r_{litter})} + (L + S)r''} \quad (3.4)$$

where q_{atm} is the atmospheric specific humidity, $q_{sat}^{T_v}$ is the saturation specific humidity at the vegetation temperature, q_g is the specific humidity of the ground, r_{aw} is the aerodynamic resistance to water vapour transfer from the vegetation to the air, r'_{aw} is the aerodynamic resistance to water vapour transfer between the ground and the vegetation, r_{litter} is a resistance for the plant litter layer, β_{soi} is an empirical function of soil water content and r'' is determined from contributions by wet leaves and transpiration and limited by available water and potential evaporation.

θ_{atm} and q_{atm} is calculated from the atmospheric forcing data and do not differ between PFTs. $LAI + SAI$ on the other hand will differ. So will all the aerodynamic resistances r , T_v , T_g , $q_{sat}^{T_v}$ and q_g because these depend on parameters that differ between PFTs.

The aerodynamic resistances are calculated from Monin-Obukhov similarity theory and differ between PFTs depending on the aerodynamic parameters (see subsection 4.1.1), the height of the vegetation and the leaf and stem area indices. Of these, the most important parameters for the resistances are the vegetation height and the ratio of momentum roughness length to canopy top height, both of which gives increased resistances when decreased.

The change in T_v for each time step is calculated from the vegetation fluxes of the energy balance and how these changes with temperature as

$$\Delta T_v = \frac{S_v - L_v - H_v - \lambda E_v}{\frac{\partial L_v}{\partial T_v} + \frac{\partial H_v}{\partial T_v} + \frac{\partial \lambda E_v}{\partial T_v}} \quad (3.5)$$

The one-dimensional form of the heat equation is given as

$$c \frac{\partial T}{\partial t} = \frac{\partial}{\partial z} \left[\lambda \frac{\partial T}{\partial z} \right] \quad (3.6)$$

where c is the volumetric snow/soil heat capacity ($\text{J m}^{-3} \text{K}^{-1}$), t is time and λ is the thermal conductivity ($\text{W m}^{-1} \text{K}^{-1}$). The soil temperature is calculated by numerically solving this equation, with the ground heat flux as the boundary condition for heat into the top soil. The ground heat flux is calculated from the fluxes at the ground as

$$G = S_g - L_g - H_g - \lambda E_g \quad (3.7)$$

The ground temperature is the soil temperature of the top layer.

The specific humidity and saturated specific humidity are calculated from the atmospheric forcing and the respective temperature.

Surface and 2-metre Temperature

The surface temperature at the virtual surface is calculated from the potential temperature of the atmosphere, the ground temperature and the vegetation temperature as

$$T_s = \frac{\frac{\theta_{atm}}{r_{ah}} + \frac{T_g}{r'_{ah}} + \frac{(LAI+SAI)T_v}{r_b}}{\frac{1}{r_{ah}} + \frac{1}{r'_{ah}} + \frac{LAI+SAI}{r_b}} \quad (3.8)$$

As seen from the equation, the importance of each of the three temperatures increase with decreasing aerodynamic resistance to sensible heat transfer and with increasing leaf and stem area index for the vegetation temperature. For bare ground the surface temperature is the same as the ground temperature.

Just like the surface temperature is calculated at the virtual surface, the 2-metre temperature is calculated 2 metres above the virtual surface.

$$T_{2m} = \theta_s + \frac{\theta_*}{k} \left[\ln \left(\frac{2 + z_{0h}}{z_{0h}} \right) - \Psi_h \left(\frac{2 + z_{0h}}{L} \right) + \Psi_h \left(\frac{z_{0h}}{L} \right) \right] \quad (3.9)$$

where $\theta_s = T_s$, θ_* is the temperature scale from the Monin-Obukhov similarity theory, z_{0h} is the roughness length for sensible heat and L is the Monin-Obukhov length which indicates the stability of the lower atmosphere.

$$\Psi_h(\zeta) = 2 \ln \left(\frac{1 + x^2}{2} \right) \quad (3.10)$$

where $x = (1 - 16\zeta)^{1/4}$.

The 2-metre temperature is also related to the surface temperature and the air temperature through the temperature scale θ_* which is proportional to $(\theta_{atm} - \theta_s)$.

Radiative Transfer in Vegetation

The radiative transfer in the vegetation is described by the following two-stream approximation proposed by Dickinson (1983) and described by Sellers (1985):

$$-\bar{\mu} \frac{dI \uparrow}{d(LAI + SAI)} + [1 - (1 - \beta)\omega]I \uparrow - \omega\beta I \downarrow = \omega\bar{\mu}K\beta_0 e^{-K(LAI+SAI)} \quad (3.11)$$

$$\bar{\mu} \frac{dI \downarrow}{d(LAI + SAI)} + [1 - (1 - \beta)\omega]I \downarrow - \omega\beta I \uparrow = \omega\bar{\mu}K(1 - \beta_0)e^{-K(LAI+SAI)} \quad (3.12)$$

where $I \uparrow$ and $I \downarrow$ are the upward and downward diffuse radiative fluxes per unit incident flux, respectively. LAI and SAI are the exposed leaf and stem area indexes, $\bar{\mu}$ is the average inverse diffuse optical depth per unit leaf and stem area, ω is the scattering coefficient, β and β_0 are upscatter parameters for diffuse and direct radiation respectively and K is the optical depth of direct beam per unit leaf and stem area. $e^{-K(LAI+SAI)}$ is the direct beam flux per unit incident flux transmitted through the canopy.

Equation (3.11) and (3.12) describes the vertical profiles for the normalised upward and downward diffuse fluxes, using leaf and stem area as a vertical coordinate. Both area indices are treated equally in the equation and depend on the height above the ground, z . The closer to the ground, the larger leaf and stem area indices. Looking at equation (3.11) we see that the first term on the left hand side of the equation is the normalised upward diffuse radiative fluxes derived with respect to the leaf and stem area index. Since the upward diffuse flux increases with height, and leaf and stem area index decreases with height, it follows that the upward diffuse flux decreases with increasing leaf and stem area index. The second term represents the part of the upward diffuse flux that is rescattered upward after interacting with the vegetation and the third term is the upward scattered part of the downward diffuse flux. On the right hand side is the upward scattered part of the direct beam flux.

Equation (3.12) is similar to equation (3.11). The terms on the left hand side are the derivative of the normalised downward diffuse radiative flux per leaf and stem area, the upward rescattered part of the downward diffuse flux, the upscattered

part of the upward diffuse flux. One the right hand side is the downward scattered part of the direct beam flux.

The scattering coefficient in the vegetation is

$$\omega_\lambda = \alpha_\lambda + \tau_\lambda \quad (3.13)$$

where α_λ and τ_λ is weighted combinations of leaf and stem reflectances and transmittances, respectively, and functions of PFT. The λ signifies that the parameters are dependent on wavelength.

The upscatter of diffuse radiation is given by

$$\omega_\lambda \beta_\lambda = \frac{1}{2} [\alpha_\lambda + \tau_\lambda + (\alpha_\lambda - \tau_\lambda) \cos^2 \bar{\theta}] \quad (3.14)$$

where $\bar{\theta}$ is the angle between the normal of the leaf and the vertical (Sellers, 1985). In CLM, $\cos \bar{\theta}$ is approximated by

$$\cos \bar{\theta} = \frac{1 + \chi_L}{2} \quad (3.15)$$

where χ_L is the deviation of leaf angles from a random distribution with +1 for horizontal leaves, 0 for randomly distributed leaves and -1 for vertical leaves. See section 4.3 for parameter values used for lichens.

3.1.3 Model Setup

The model was run in offline mode, meaning that it is uncoupled from other components of CESM. Most importantly this means that the model did not have an active atmospheric model but instead supplied the atmospheric forcing from observed data sets (incident solar radiation, precipitation, specific humidity, surface pressure, temperature and wind). The standard forcing for CLM4.5, CRUNCEP (Kluzek, 2013), was used. It spans 110 years from 1901 to 2010, with a resolution of $0.5^\circ \times 0.5^\circ$ and observations every six hours.

Since the model was run in offline mode there was no way for the model to change the atmospheric input data. While the model calculated fluxes into the atmosphere and a 2-metre temperature of the atmosphere, changes on the surface did not change the atmospheric forcing. This is a limitation to the model runs and will introduce some errors, which is discussed in chapter 5.

Idealised Single Cell

The first model runs performed were what will be referenced as *idealised single cell* simulations. That is simulations performed using a single column with only one PFT covering the entire area of the cell. The resolution of the column was $0.005^\circ \times 0.005^\circ$ and the position chosen was 69°N , 23°E . The motivation behind this type of simulations are that they are simple and very fast to run, making it possible to do many simulations. Additionally, the results are easier to interpret when there is only one PFT and only one column. Two PFTs can easily be compared by doing two identical runs with different PFTs and comparing the results. As we are interested in how lichen compares with other PFTs that could possibly be replacing lichen, I chose to look at shrubs, grass and bare ground. The shrub PFT was broadleaf deciduous boreal shrub and the grass PFT was arctic grass. These were chosen because they were the shrub and grass PFT that were in the model's PFT distribution for the column (based on the Moderate Resolution Imaging Spectroradiometer (MODIS) data).

These model runs were used to obtain several results. Firstly, they were used to specify a first draft of the parameters for lichen, their simplicity and speed needed when tuning the parameters. They were used for sensitivity tests, to look at the daily variations for the various PFTs and compare these, and to calculate monthly averages for lichen and other PFTs. The high speed made it possible to run for many years.

Regional Run

The other type of model runs performed in this thesis were regional runs, that is model runs for a larger area divided into several grid cells. The area was 22.2°E to 25.9°E , 68.8°N to 69.9°N . This is 145×120 km, which was divided into a 20×20 grid. This covers large parts of mainland Finnmark as seen in figure 3.2. This type of model run was used together with the estimated lichen heath cover described in subsection 3.2.1.

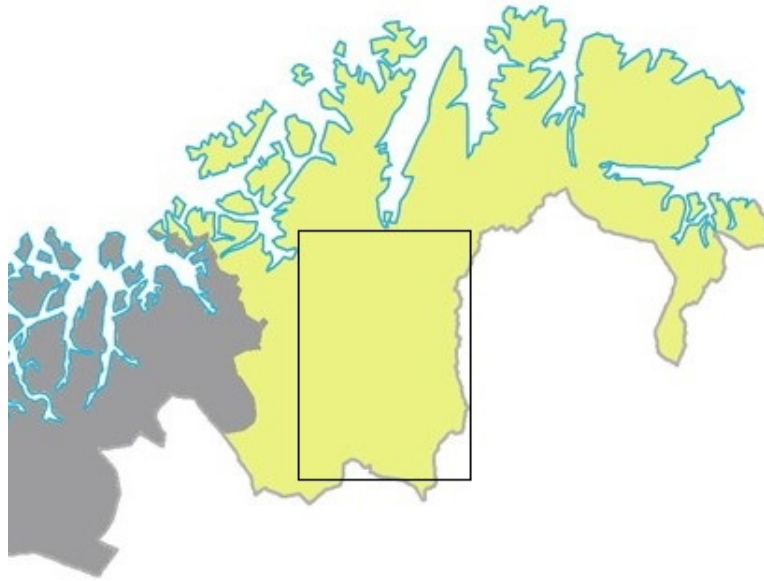


Figure 3.2: The study area used in this thesis. Modified from Kartverket (2018)

3.2 Model Input

3.2.1 Lichen Heath Cover from Distribution Modelling

Distribution modelling is a method used to predict potential occurrence of vegetation types in areas that are not mapped. This is done by relating the known occurrences of vegetation types to environmental variables. Of the mapped areas, some are used to train the model to make the occurrences a function of the environmental variables. The rest of the areas with data are then used to test the model. Finally, the model is used to find the potential distribution of vegetation types outside the known areas by making use of the environmental variables.

I have used the potential occurrence of lichen heath from a such a model as described above, provided by Peter Horvath. For the vegetation data the *Norwegian area frame survey of land cover and outfield land resources* (AR18X18) was used. This uses a systematic sampling technique with 0.9 km² sample plots at 18 km intervals and 57 land use types (for more details see Strand, 2013). The environmental variables are resolved at 100 x 100 metres and consist of 136 variables from five categories: Climatic, Hydrological, Topographic, Land use and Geological (Peter Horvath, personal communication).

Lichen is found in most of the vegetation types in the model but only dominates

a few (Anders Bryn, personal communication). Because lichens that are largely covered by trees or shrubs will have different properties from lichen itself, most other vegetation types are more difficult to include. Since lichen heath is the vegetation type having the largest proportion of lichen (Anders Bryn, personal communication) this is the vegetation type I have used.

Since the model gives the probabilities of finding each vegetation type, the data from the distribution modelling must be converted into fractional cover to be used in CLM. This is not straight forward, but here data from Bryn et al. (2018) about the amount of lichen heath in Norway was used. They found that lichen heath covers 6% of the area of Norway. This was used in a simple binary conversion such that the grid cells in Norway with the 6% highest probabilities for lichen heath got 100% cover and the rest got no lichen heath cover. The resulting cover of lichen heath for the study area was 34%, distributed as shown in figure 3.3.

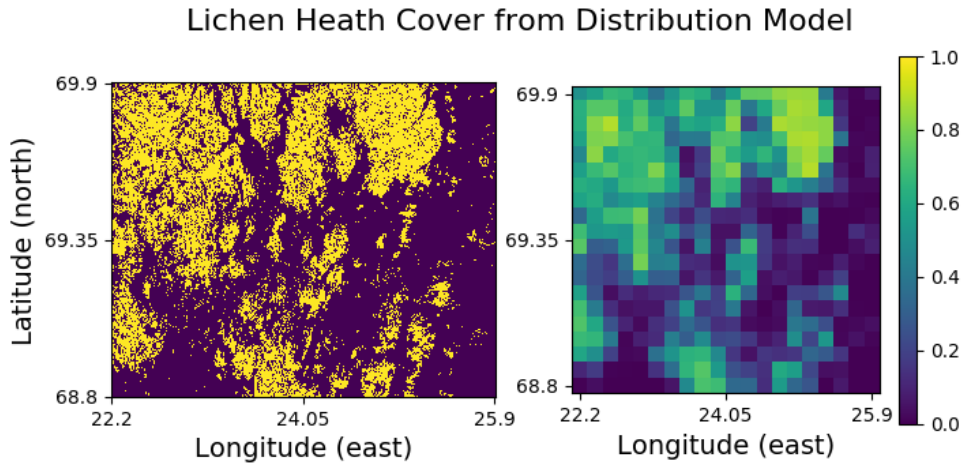


Figure 3.3: Lichen heath cover from distribution modelling. The left panel show the original resolution with the binary distribution of either 100% or 0% lichen heath in each grid cell. The right panel shows the aggregated lichen heath cover for a 20x20 grid to be used in CLM 4.5.

Lichen heath does not consist of 100% lichen. The composition will vary but I have assumed that 50% lichen, 25% bare ground and 25% shrubs is reasonable (Anders Bryn, personal communication). For the grid columns not covered by lichen heath, I used the vegetation distribution that is already part of the model (based on MODIS data). For the columns that are partly lichen heat I also used this data: I assumed that lichen heath does not grow where there are trees and

therefore hold tree fractions constant while the rest of the PFTs were scaled down so that all the vegetation added up to 100%.

3.3 Canopy Water Experiment

I had access to two lichen samples (shown in figure 3.4), and used these to do some experiments. I wanted to quantify the maximum canopy water for lichens, and compare it with the value I used in the model (see subsection 4.4.1). I also wanted to look at the timescale of drying, how fast lichen dries and how the drying change with time as the lichen dries. Comparing the evaporation rate of an actual lichen sample with the model rate should give me a good indication of how realistic the model simulates evaporation from lichen.



(a) Sample 1 - *Cladonia Stellaris*.



(b) Sample 2.

Figure 3.4: The two lichen samples used in the experiment.

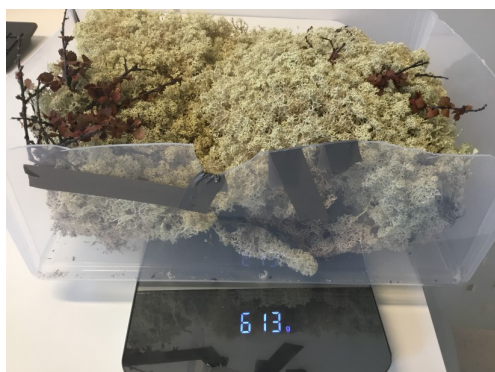
The lichen samples had been inside for months and was completely dry. That was the starting condition, although this was probably much drier than what we would find in most places (except during unusual drying periods). The lichen was placed in a plastic box so that water would not evaporate from the sides or the bottom of the lichen, as we would expect to be the case in nature where lichens typically grow as a continuous cover. I had the top edge of the box removed, making it approximately the same height as the lichen sample, so that air was free to move over the top of the lichen. Then I made small holes in the bottom, so that excess water could drip out of the box. Lichen sample 1 in the finished box is showed in figure 3.5.

I first weighted and measured the lichen samples while they were completely dry, as shown in figure 3.6a. Then I filled the samples with as much water as they



Figure 3.5: The lichen sample at the start of the experiment. It was placed in a plastic box of approximately same height as the lichen with holes in the bottom.

could take up. This was done by filling on a lot of water and letting it drip off overnight inside a plastic bag to stop water from evaporating (figure 3.6b). The resulting water was taken as the maximum canopy water and I weighed and measured it again. From this I calculated how much water lichen can hold, i.e. the maximum canopy water.



(a) Weighing of lichen after it had dried inside for months.



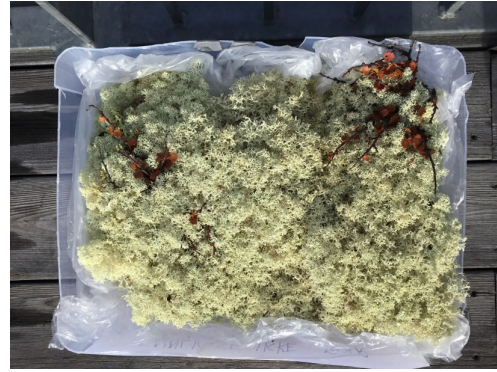
(b) After being filled with water the lichen dripped of inside a plastic bag.

Figure 3.6: Preparations for the drying experiment.

I let the lichen stay outside, and weighed it regularly, every 30 minutes during the day (not during the night). The first measurements started 18.04.18 at 08:20 and ended 20.04.18 at 14:00 for sample 1. (Sample 2 was also measured in this interval but dried faster.) Lichen sample 1 at the start of this period is shown in figure 3.7a.



(a) Lichen without plastic. (Start 18.04.18.)



(b) Lichen with plastic. (Start 25.04.18.)

Figure 3.7: Lichen sample 1 at the beginning of the drying periods.

Because the lichen samples started to dry at the sides, becoming just as dry as the top, the experiment was performed a second time. The difference from the first time was that transparent soft plastic was put between the box and the lichen as seen in figure 3.7b. This was done to avoid circulation of air between the lichen and the box. The measurements for this experiment started 25.04.18 at 08:40 and ended 27.04.18 at 15:10 for lichen sample 1. (Sample 2 was also measured within this period.)

Chapter 4

Parameters for Lichen

In order to represent lichens as a PFT, the parameters define the PFT must be set. To avoid problems with the code the simplest option was to modify a pre-existing PFT that was not needed for my thesis to fit lichen. Tropical broadleaf evergreen tree is a PFT that should not occur in Finnmark, or any other high latitude or mountain environments, and I therefore changed this PFT into lichen. A description of all the parameter choices is given in the following sections. Additionally, a concise overview of all the parameters, their value and where they are set can be found in appendix A.

Note that all parameters related to photosynthesis and transpiration are ignored because these will not be used for lichen when $LAI = 0$ (see section 4.1). Also, all parameters related to carbon and nitrogen pools, fire and dynamic vegetation are not included either because these are not used by the satellite phenology sub-mode.

4.1 Morphology

Plant morphology is the physical appearance of the plant, such as size and structure. In CLM4.5 there are parameters to describe height, root distribution, leaf and stem area and aerodynamic parameters.

For lichen, canopy top height is set to 0.1 metres, as mentioned by Jonsson et al. (2008) as a reasonable top height for *Cladonia* lichens, and bottom height to 0.01 metres.

There are two root distribution parameters for each PFT that control the uptake

of water from the soil. These are adapted from the root distribution in Zeng (2001):

$$Y = 1 - \frac{1}{2}(e^{-az} + e^{-bz}) \quad (4.1)$$

where Y is the cumulative root fraction from the surface to depth z and a and b are the root distribution parameters that depend on the vegetation. Since lichens does not have roots (see section 2.2) the root fraction is set to zero in the entire soil column.

Leaf area index (LAI) and stem area index (SAI) is defined as the leaf and stem area per unit ground area, and defines the amount of leaves and stems. It is set for each month in CLM4.5 but since lichen does not change much throughout the year it is reasonable to set the same value for every month.

CLM4.5 treats LAI and SAI equally for almost all calculations. The exceptions are photosynthesis and transpiration, where only LAI is included, and reflectances and transmittances, which are given separately for leaves and stems (see section 4.3). I do not want to include transpiration, and since photosynthesis is closely linked to transpiration, I chose to remove both of these, by setting $LAI = 0$ (see also section 4.2).

To decide the SAI value for lichen I used other variables that depend on this parameter. Most variables can be tuned by other parameters in addition to $LAI + SAI$ but the emissivity depends solely on $LAI + SAI$ (see equation 3.2). In the absence of any information on the emissivity of lichen I assume that the emissivity is the same for lichen as for shrubs/grass. To obtain this I must have SAI for lichen equal to $LAI + SAI$ for shrubs and grass. As mentioned, these vary through the year but since emissivity is most important during summer I chose to use the $LAI + SAI$ value for July. This is approximately 2.5 for shrubs and grass, and consequently I set $SAI = 2.5$ for lichen. I then tuned any other variables that depend on $LAI + SAI$ by other parameters.

4.1.1 Aerodynamic Parameters

The aerodynamic parameters needed for lichen in CLM4.5 are the ratio of momentum roughness length to canopy top height R_{z0m} , the ratio of displacement height to canopy top height R_d , and the characteristic dimension of the leaves in the direction of wind flow d_{leaf} . Roughness length and displacement height are described in subsection 2.1.2.

The leaf boundary layer is a thin, still layer around leaves and stems where heat and water vapour must be transferred by molecular conduction *Referanse!*. The

leaf boundary layer resistance, r_b , is proportional to the square root of d_{leaf} and inversely proportional to the square root of the magnitude of the wind velocity on the leaves. Assuming that the leaf boundary layer resistance for lichens will be similar to that for other vegetation seems natural. Since d_{leaf} is set to 0.04 for all PFTs (Keith W. Oleson, 2013), I will use the same value for lichen.

Since roughness length and displacement height typically depend on the height of the vegetation (see subsection 2.1.2), it is natural to assume that the ratio of momentum roughness length and displacement height to canopy top height will be quite similar for all types of vegetation. For trees R_{z0m} is set to 0.055 or 0.075 and for lower vegetation, like shrubs and grass, it is set to 0.120. R_d is set to 0.67 for trees and 0.68 for lower vegetation. Since lichen is a low PFT I chose to set the parameters for lichen similar to the lower vegetation, that is $R_{z0m} = 0.120$ and $R_d = 0.68$.

4.1.2 Vegetation Burial by Snow

The amount of LAI and SAI that is exposed depends on how much of the vegetation that is buried by snow as

$$A = A^*(1 - f_{veg}^{sno}) \quad (4.2)$$

where A^* is the leaf and stem area before snow burial, A is the leaf and stem area after snow burial and f_{veg}^{sno} is the vertical fraction of the vegetation that is covered by snow

$$f_{veg}^{sno} = \begin{cases} \frac{z_{sno} - z_{bot}}{z_{top} - z_{bot}} & \text{for trees and shrubs} \\ \frac{\min(z_c, z_{sno})}{z_c} & \text{for grasses and crops} \end{cases} \quad (4.3)$$

where $0 \leq f_{veg}^{sno} \leq 1$, $z_{sno} - z_{bot} \geq 0$, z_{sno} is the snow depth and $z_c = 0.2$ metres is the snow depth when grasses and crops will be completely buried by snow (Keith W. Oleson, 2013). Since lichen has been set to 0.1 metres (and have z_{bot} close to zero) I have let lichen be buried by snow similar to trees and shrubs so that it will be buried before the snow depth is 0.2 metres.

4.2 Photosynthesis

Photosynthesis is important in CLM4.5 for two reasons. To calculate carbon fluxes and for transpiration. Since I am not looking at carbon fluxes and I assume

that lichens have no transpiration (no roots) I have removed photosynthesis from lichen (see section 4.1). Parameters for photosynthesis are then irrelevant.

4.3 Optical Properties

As mentioned, the lichens in focus in this study are light in colour, and one would therefore expect them to have higher albedo than other types of vegetation. Huemmrich et al. (2013) looked at optical properties of arctic vegetation, including lichen, and took in-situ spectral reflectance measurements as can be seen in figure 4.1. The figure shows that lichen should have a higher reflectance than vascular vegetation in the visible spectrum but somewhat lower reflectance in the near infrared.

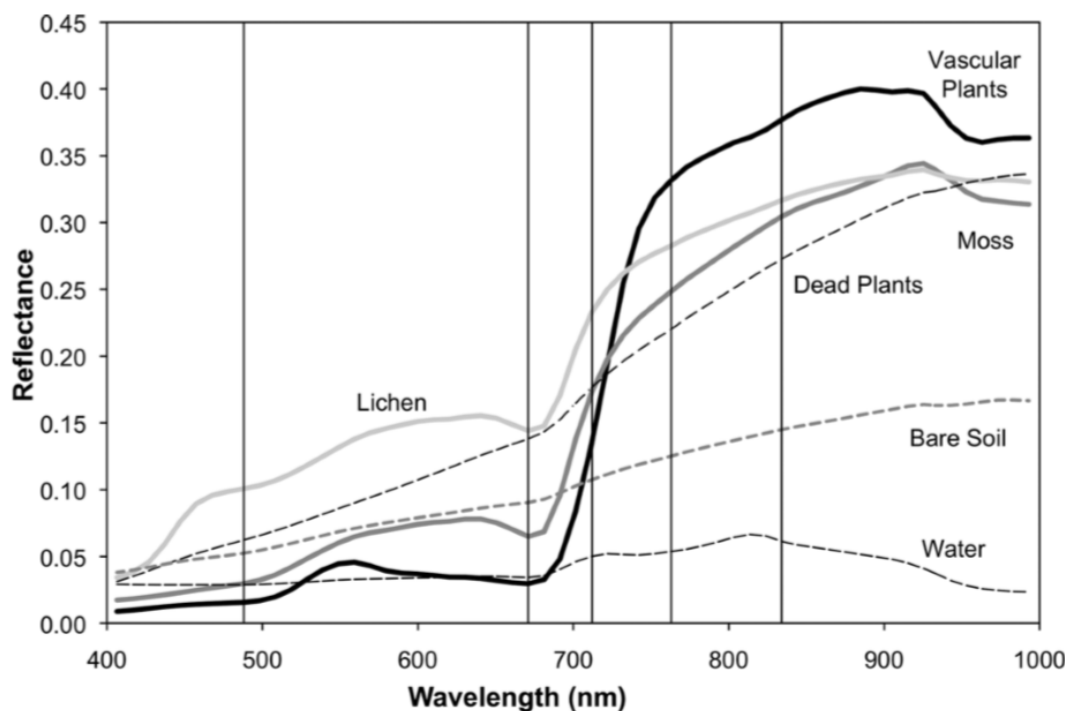


Figure 4.1: Spectral reflectance for various vegetation. Reprinted from Huemmrich et al. (2013).

The optical parameters in CLM4.5 are reflectance and transmittance for leaves and stems, and a parameter for deviation of leaf angles from a random distribution χ_L (see subsection 3.1.2). Instead of having reflectance and transmittance as functions of wavelength, CLM4.5 has two values for each, one for the visible part

of the spectrum and one for the near infrared part. The values for the different PFTs are given in table 4.1, including the values chosen for lichen. Because lichen is represented as stems only (see section 4.2), the parameters for leaves were ignored for lichen, and since the lichen thallus seems to be randomly distributed (see figures in section 3.3) I have assumed that $\chi_L = 0.01$ is reasonable.

Table 4.1: Optical parameters for all PFTs. χ_L is the deviation of leaf angles from a random distribution, α is reflectance and τ is transmittance. leaf and stem indicate whether the reflectance or transmittance is for leaves or stems, and vis and nir stands for visible and near infrared respectively. Reproduced from Keith W. Oleson (2013).

PFT	χ_L	α_{vis}^{leaf}	α_{nir}^{leaf}	α_{vis}^{stem}	α_{nir}^{stem}	τ_{vis}^{leaf}	τ_{nir}^{leaf}	τ_{vis}^{stem}	τ_{nir}^{stem}
NET Temperate	0.01	0.07	0.35	0.16	0.39	0.05	0.10	0.001	0.001
NET Boreal	0.01	0.07	0.35	0.16	0.39	0.05	0.10	0.001	0.001
NDT Boreal	0.01	0.07	0.35	0.16	0.39	0.05	0.10	0.001	0.001
BET Tropical	0.10	0.10	0.45	0.16	0.39	0.05	0.25	0.001	0.001
BET Temperate	0.10	0.10	0.45	0.16	0.39	0.05	0.25	0.001	0.001
BDT Tropical	0.01	0.10	0.45	0.16	0.39	0.05	0.25	0.001	0.001
BDT Temperate	0.25	0.10	0.45	0.16	0.39	0.05	0.25	0.001	0.001
BDT Boreal	0.25	0.10	0.45	0.16	0.39	0.05	0.25	0.001	0.001
BES Temperate	0.01	0.07	0.35	0.16	0.39	0.05	0.10	0.001	0.001
BDS Temperate	0.25	0.10	0.45	0.16	0.39	0.05	0.25	0.001	0.001
BDS Boreal	0.25	0.10	0.45	0.16	0.39	0.05	0.25	0.001	0.001
C ₃ arctic grass	-0.30	0.11	0.35	0.31	0.53	0.05	0.34	0.120	0.250
C ₃ grass	-0.30	0.11	0.35	0.31	0.53	0.05	0.34	0.120	0.250
C ₄ grass	-0.30	0.11	0.35	0.31	0.53	0.05	0.34	0.120	0.250
Crop	-0.30	0.11	0.35	0.31	0.53	0.05	0.34	0.120	0.250
Lichen	0.01	-	-	0.34	0.37	-	-	0.120	0.250

To obtain the wanted optical properties for lichen, the values in table 4.1 cannot be compared directly with the figure or with each other. Instead the figure must be compared with the computed albedo from CLM4.5 and the parameters chosen such that the main points in the figure are reproduced. Output from the model is reflected and incoming solar radiation for direct visible, diffuse visible, direct infrared and diffuse infrared radiation. These are calculated from the variables given in table 4.1 and from the given leaf and stem area index, that is $LAI = 0$ and $SAI = 2.5$ for lichen (see section 4.1 about LAI and SAI). From this the albedo is calculated as the sum of direct and diffuse reflected radiation divided by the sum of direct and diffuse incoming radiation at the surface. Albedo for four different PFTs are given in table 4.2. These albedos were calculated by

taking the average of the first 10 days of July 1981. The reason behind taking an average is the way CLM4.5 calculates reflectance: for direct beam radiation the reflectance varies through the day depending on the angle of the incoming radiation.

Comparing table 4.2 with figure 4.1 is not necessarily easy because the model gives an average for near infrared and visible light based on the amount of incoming radiation. From the figure we can discern an approximate difference between lichen and vascular plants. In the near infrared lichen seems to be 0.05 below vascular plants. For visible light lichen is approximately 0.1 above vascular plants. As seen from the albedos in table 4.2, the optical variables for lichen from table 4.1 is chosen to reproduced these properties.

Table 4.2: Albedo for the infrared part, the visible part and the full spectrum for BDT Boreal, BDS Boreal, arctic grass and lichen. Calculated from the average of 1.-10. July 1981.

Plant Functional Type	Near infrared	Visible	Albedo
BDT Boreal	0.30	0.07	0.18
BDS Boreal	0.28	0.05	0.16
C ₃ arctic grass	0.34	0.07	0.20
Lichen	0.26	0.17	0.22

For bare ground the optical parameters are different. The ground does not have a transmittance, nor leaves or stems. Instead the albedo of the soil is given. This is given similarly to the vegetation with one value for the visible part of the spectrum and one for the near infrared. The ground can have 20 different soil colours, each with different albedo. The soil colours range from 1 to 20 with 1 being the lightest and 20 the darkest. For each soil colour the albedo is given both for dry and saturated conditions, letting the albedo vary depending on how wet the ground is.

For vegetation CLM4.5 does not differentiate between wet and dry. Rees et al. (2004) looked at the difference in reflectance spectra between dry and wet lichens and concluded that the difference is generally small ($\pm 5\%$), with the dry lichen typically being somewhat more reflecting. I therefore assume that this is not an important source of error.

4.4 Hydrology

The water balance in CLM4.5 is

$$\Delta W_{can} + \Delta W_{scf} + \Delta W_{sno} + \sum_{i=1}^N (\Delta w_{liq,i} + \Delta w_{ice,i}) + \Delta W_a = (q_{rain} + q_{sno} - E_v - E_g - q_{over} - q_{h2osfc} - q_{drai} - q_{rgwl} - q_{snwcp,ice}) \Delta t \quad (4.4)$$

where ΔW_{can} is changes in canopy water, ΔW_{scf} is changes in surface water, ΔW_{sno} is changes in snow water, ΔW_a is changes in water in the unconfined aquifer, $\Delta w_{liq,i}$ and $\Delta w_{ice,i}$ is the changes in soil water and ice in layer i , N is the number of hydrologically active soil layers, q_{rain} is the liquid part of the precipitation, q_{sno} is the solid precipitation, E_v and E_g is the evapotranspiration from the vegetation and ground, respectively, q_{over} is surface runoff, q_{h2osfc} is runoff from surface storage, q_{drai} is subsurface drainage, q_{rgwl} and $q_{snwcp,ice}$ is other types of liquid and solid runoff and Δt is the model time step (Keith W. Oleson, 2013). All terms on the left hand side is measured in kg m^{-2} while the unit of the terms inside the parenthesis on the right hand side is $\text{kg m}^{-2} \text{s}^{-1}$.

The precipitation in CLM4.5 is either intercepted by the vegetation, falls directly to the surface or drips of the vegetation (Keith W. Oleson, 2013). Interception, q_{intr} , is given by

$$q_{intr} = \alpha(q_{rain} + q_{sno})[1 - e^{-0.5(LAI+SAI)}] \quad (4.5)$$

where LAI and SAI is the exposed leaf and stem area index. α is set to 0.25 to reduce canopy interception, reflecting that rainfall does not necessarily wet the entire leaf. This allows for more transpiration and gives a more realistic relationship between evaporation and transpiration from vegetation (Lawrence et al., 2007).

Throughfall, the part of the precipitation that is not intercepted, for liquid and solid precipitation is given by

$$\begin{aligned} q_{thru,liq} &= q_{rain} \alpha \{1 - [1 - e^{-0.5(LAI+SAI)}]\} \\ q_{thru,sol} &= q_{sno} \alpha \{1 - [1 - e^{-0.5(LAI+SAI)}]\} \end{aligned} \quad (4.6)$$

Dripping is given by

$$\begin{aligned} q_{drip,liq} &= \frac{W_{can}^{intr} - W_{can,max}}{\Delta t} \frac{q_{rain}}{q_{rain} + q_{sno}} \\ q_{drip,sol} &= \frac{W_{can}^{intr} - W_{can,max}}{\Delta t} \frac{q_{sno}}{q_{rain} + q_{sno}} \end{aligned} \quad (4.7)$$

where $W_{can}^{intr} = W_{can}^n + q_{intr}\Delta t$ is the canopy water after accounting for interception, W_{can}^n is the canopy water from the previous time step n and $W_{can,max}$ is the maximum canopy water.

The maximum canopy water, liquid or solid, is

$$W_{can,max} = p(LAI + SAI) \quad (4.8)$$

with $p = 0.1 \text{ kg m}^{-2} = 0.1 \text{ mm}$ (Dickinson et al., 1993).

The canopy water in time step $n + 1$ is updated as

$$W_{can}^{n+1} = W_{can}^n + q_{intr}\Delta t - (q_{drip,liq} + q_{drip,sol})\Delta t - E_v^w \Delta t \quad (4.9)$$

where E_v^w is the flux of water vapour from vegetation.

4.4.1 Maximum Canopy Water

Bello and Arama (1989) measured an average maximum canopy water of 4.21 mm = 4.21 kg/m² for lichen. Given a leaf area index of zero and a stem area index of 2.5 m²/m², the value of p must be changed to 1.68 kg/m² in CLM4.5 for lichen to obtain the same maximum canopy water as described by Bello and Arama (1989).

Figure 4.2 shows a constructed rainfall event on 1.-4. of July 2008. A rainfall of 0.001 mm/s = 3.6 mm/h is added between hour 6 and 18. The water is added to make sure the canopy water reaches its maximum. The results from the old p -value are included as dotted lines to make it easy to compare.

There is definitely a change in both canopy water and evaporation. The canopy water peak has increased from 0.25 mm to 4.2 mm, both cases reaching the maximum canopy water. It is clear that the model responds to the new p -value. The evaporation from the vegetation has also changed. From around hour 20 the latent heat flux is considerably higher due to much more evaporation from the canopy. This is because of the increased amounts of available water in the canopy as it takes longer for the canopy to dry when it contains more water.

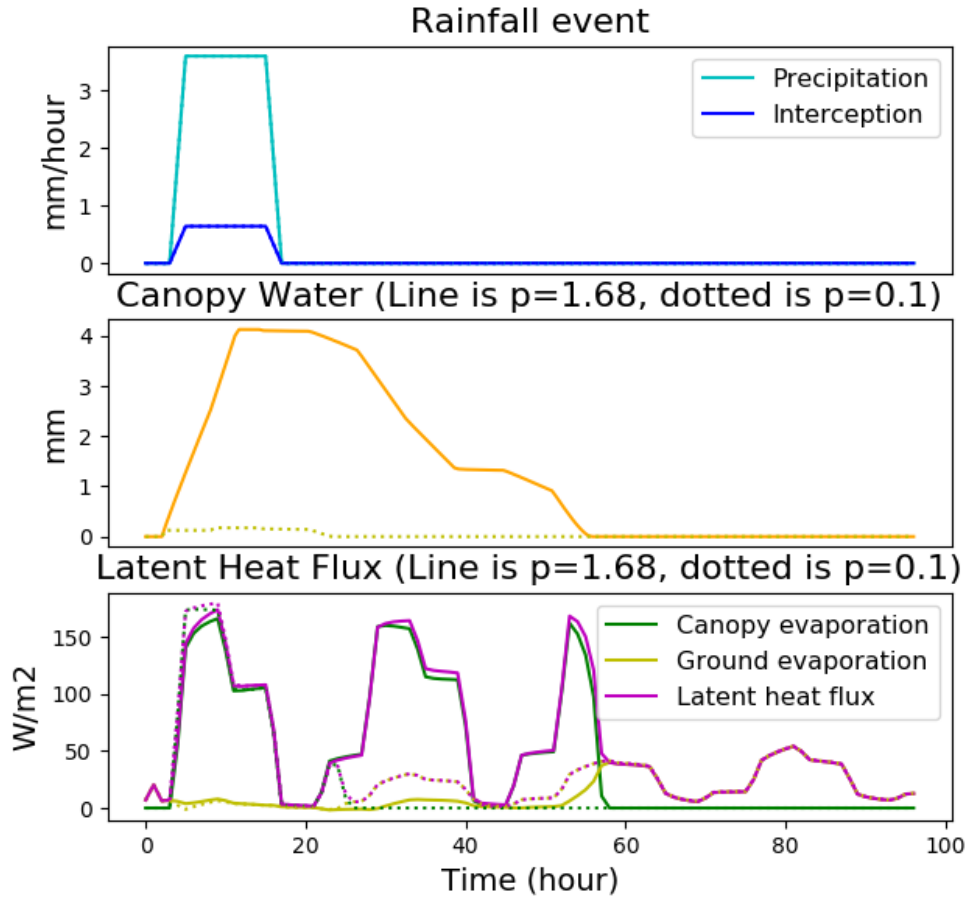


Figure 4.2: Comparison of canopy water and latent heat fluxes for different maximum canopy water. The solid lines show $p=1.68$ (new value) and the dotted lines show $p=0.1$ (old value).

Top Panel: Precipitation and interception by the vegetation, measured in mm/hour.

Middle panel: Canopy water measured in mm.

Bottom panel: Canopy evaporation, ground evaporation and total latent heat flux (sum of canopy and ground evaporation), measured in W/m^2 .

4.4.2 The Alpha Parameter

As mentioned alpha was set to 0.25 in equations 4.5 and 4.6 to better reflect the transpiration and the fraction of the leaves getting wet. However, lichens have

no transpiration (see section 4.1) and absorb water quite similar to a sponge, so it is reasonable to assume that the entire lichen gets wet. Based on these arguments it makes sense to change α to 1.

Figure 4.3 shows exactly the same rainfall event as figure 4.2 but with $p=1.68$ mm and α set to 1. Results for the old α value of 0.25 is plotted as dotted lines for comparison. A larger α should make the canopy water increase faster at the beginning of the rain event, as all the water (not just 25 %) is allowed to enter the canopy water, and we see in the plot that this does indeed happen. We also see the increased interception following directly from equation 4.5.

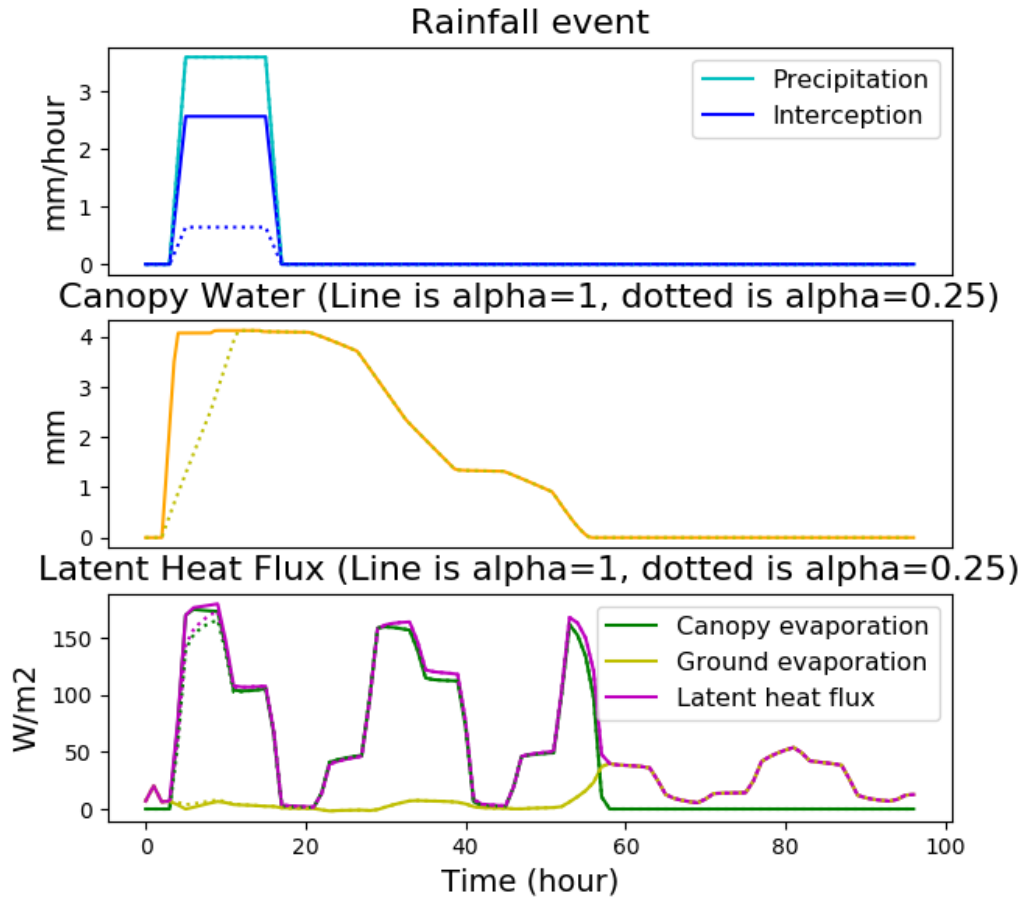


Figure 4.3: Comparing values for α . The three plots are the same as in figure 4.2 but here all lines have $p=1.68$ mm and the dotted lines are $\alpha=0.25$ while the main lines is $\alpha=1$.

Chapter 5

Results and Discussion

In this chapter I present and discuss the results, starting with sensitivity tests for the parameters. Note that throughout this chapter, comparisons between lichen and other PFTs are made as *lichen – preexisting PFT*.

5.1 Sensitivity Tests

Sensitivity tests are useful to get an understanding of how robust the choices of parameters for lichen are, and how robust the differences are between PFTs. Additionally, it can give us an understanding of how the various parameters affect the surface energy fluxes. Several tests with various parameter choices were performed using idealised single cell experiments for July 2008 with the CRUNCEP atmospheric forcing data. July was chosen because there is no snow cover, making it possible to compare the different surface energy fluxes without the influence of snow. Also the solar insolation is large this month, which should give a large effect from the optical parameters and in extension all the surface energy fluxes.

The tests are summarised in table 5.1, and chosen to represent differences in parameters that are similar to those between PFTs. In addition to these tests, the same simulation was also run with shrub, grass and bare ground to see the results from the tests in context with the differences between the PFTs. Throughout this section the lichen parameterisation described in chapter 4 is referred to as the lichen baseline.

First, figure 5.1 shows the surface energy fluxes for the four PFTs lichen, shrub, grass and bare ground. The figure makes it easy to see how large the surface

Table 5.1: Name and description of the sensitivity tests.

Name	Difference from the parameters sat in section 4.1-4.4
SAI=3.5	SAI increased from 2.5 to 3.5
SAI=1.5	SAI decreased from 2.5 to 1.5
ztop=0.5	Increased from 0.1, to match shrubs and grass
zbot=0.1	Increased bottom height to 0.1, to match shrubs
xl=0.25	χ_L increased to 0.25
xl=-0.25	χ_L decreased to -0.25
rhosvis=0.44	Increased reflectance in the visible part of the spectrum α_{vis}^{stem} by 0.1
rhosnir=0.47	Increased the reflectance in the near infrared part of the spectrum α_{nir}^{stem} by 0.1
tausvis=0.001	Removed transmittance in the visible part of the spectrum τ_{vis}^{stem} to the same as shrubs and trees
tausnir=0.001	Removed transmittance in the near infrared part of the spectrum τ_{nir}^{stem} to the same as shrubs and trees
displar=0.67	Set the displacement height to canopy top height R_d to the same value as trees.
z0mr=0.6	Halved the roughness length to canopy top height R_{z0m} , giving it a similar value to that of trees.
dleaf=0.08	Doubled the characteristic dimension of the leaves in the direction of wind flow d_{leaf}

fluxes are compared to each other, and how they differ between PFTs for this particular month. The lichen PFT here is the lichen baseline the sensitivity tests are compered with. A closer examination of the differences between lichen and the other PFTs are given in section 5.2 and 5.3.

Figure 5.2 shows the average differences in surface energy fluxes between the sensitivity tests and the lichen baseline. We see that the largest absolute changes are found in absorbed SW, while the largest relative errors are found in sensible heat flux. Note that the test results for the bottom height (zbot) and the ratio of displacement height to canopy top height are not included, as these did not give any differences in the surface energy fluxes.

It can be difficult to compare the importance of the various parameters because the importance will vary with the magnitude of the parameter perturbation. However, all the parameter perturbations here are taken as typical differences between PFTs, which means that it to some extent makes sense to compare the

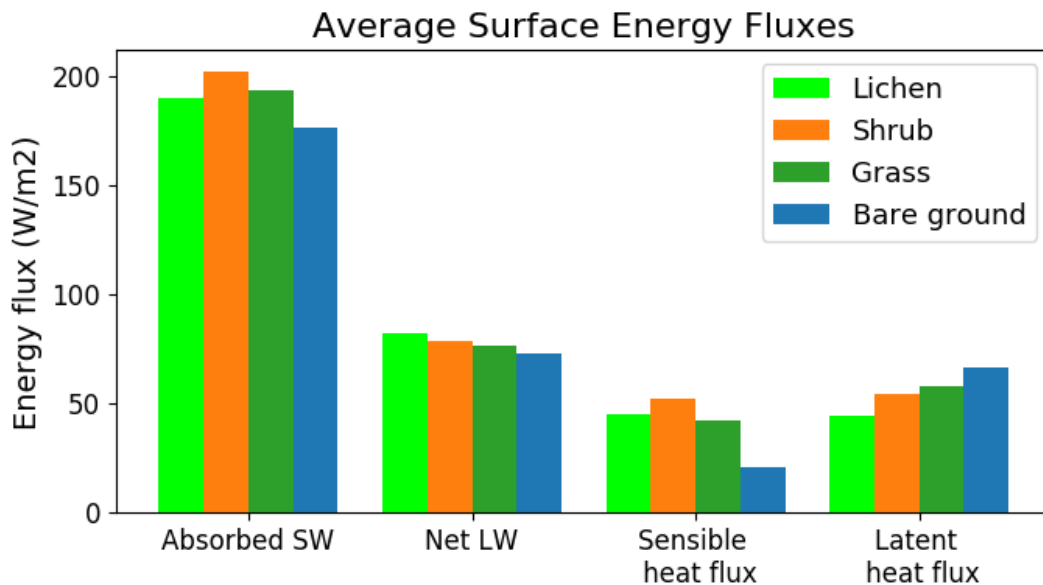


Figure 5.1: Average surface energy fluxes for lichen, shrub, grass and bare ground. The runs were performed for July 2008.

flux changes. It also explains why the differences in surface energy fluxes found in the sensitivity tests mostly are of approximately the same size as the differences between PFTs. Given that the tests are comparable, the optical parameters seem to be the most important.

Because the optical parameters decides the absorbed SW, these are clearly important for this flux. Net LW, sensible and latent heat fluxes are not directly dependent on these parameters, but we see that these fluxes also change when the optical parameters are changed. This is because changes in absorbed SW changes the amount of available energy. It is noteworthy that the transmittance for lichen was simply assumed to be the same as grass (section 4.3). One might think that lichens do not have any transmittance like shrubs, which we see from the tests have a notable effect on the surface fluxes. Also the deviation of leaf angles from a random distribution (α_l) was simply assumed to be random (0) while that may not be the case for all lichen species. However, the optical parameters were tuned to give an appropriate albedo, which is what these parameters are used to calculate, so it should not be crucial for the results.

The sensitivity tests also illustrate how parameter perturbations that initially affects the turbulent fluxes indirectly affects the net LW: As expected the aerodynamic parameters and the vegetation height influence the turbulent fluxes (see

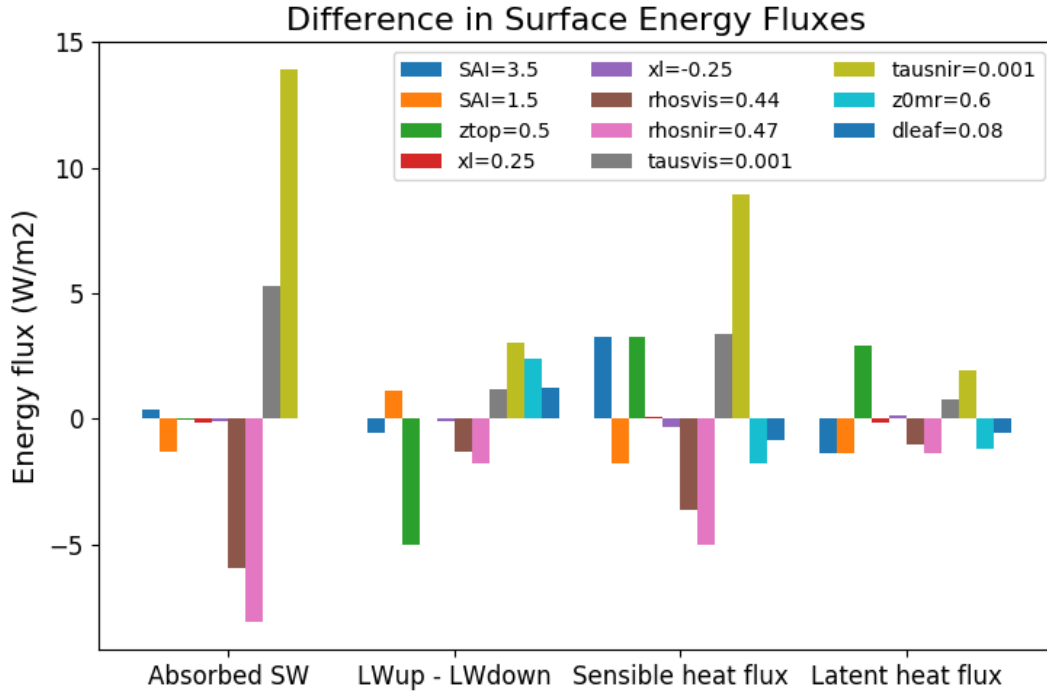


Figure 5.2: Results for the sensitivity tests. Showing the average difference in surface energy fluxes between parameter perturbations as described in table 5.1 and the lichen baseline. The tests were performed for July 2008.

subsection 3.1.2). We also see that the net LW have changes with opposite sign as a result of these perturbations, even though this flux only depends on the emissivity and the temperature. This is explained by larger (smaller) turbulent fluxes cooling the surface more (less), which reduces (increases) the upward LW.

The differences in latent heat flux for the various parameter perturbations are all less than 3 W/m^2 , which is much smaller than the differences between lichen and the other PFTs. This suggests that the differences in latent heat flux between lichen and other PFTs are a consequence of changes in the hydrological parameters or the removal of transpiration (all the sensitivity tests were without transpiration). This will be examined more closely in the following sections.

It is important to note that these are the result of one specific July, and especially the latent and sensible heat fluxes are dependent on the amount and frequency of precipitation.

5.2 Daily Variations for Single Cell

Motivation

As mentioned in the introduction I want to quantify how the surface energy fluxes differ between lichen and other PFTs that could potentially replace lichen. To do this I have used an idealised single cell experiment in CLM4.5 to see how the surface energy fluxes vary throughout the day, both in dry and wet conditions, for the various PFTs. In addition to comparing the surface energy fluxes I want to look at the timescale of drying and temperatures of the various PFTs to get a better indication of the importance of including lichen.

Setup

The experiments were run for eight days from 1st to 8th of July 2008, with hourly output for 100 % cover of either lichen, shrubs, grass and bare ground. The reason for choosing July was the same as described in section 5.1. On the 4th of July, from 00.00 to 18.00, precipitation of $0.001 \text{ mm/s} = 3.6 \text{ mm/hour}$ was added, giving a total of 64.8 mm precipitation in 18 hours. Otherwise, all precipitation was removed. This was done to ensure that both dry and wet conditions would occur. The rain was added in the middle of the period to see if the conditions after the rain period get back to the same as they were before the event. The added rainfall also ensured that the vegetation would receive enough precipitation to reach their maximum canopy water, followed by a drying period without any additional rain to complicate the comparison of drying between PFTs.

Results

Figure 5.3 shows the canopy water, the surface energy fluxes and the 2-metre and surface temperatures during the described period for lichen. All surface fluxes except absorbed shortwave radiation (SW) are positive upwards away from the surface. $LW_{up} - LW_{down}$ is the net upward longwave radiation (LW), referred to as net LW. All the results in this section are discussed from page 47.

From the figure we can see that lichen comes close to its maximum canopy water very quickly. After the rain stops, the canopy water decreases, with large decreases during the day and small decreases during the night. There are some

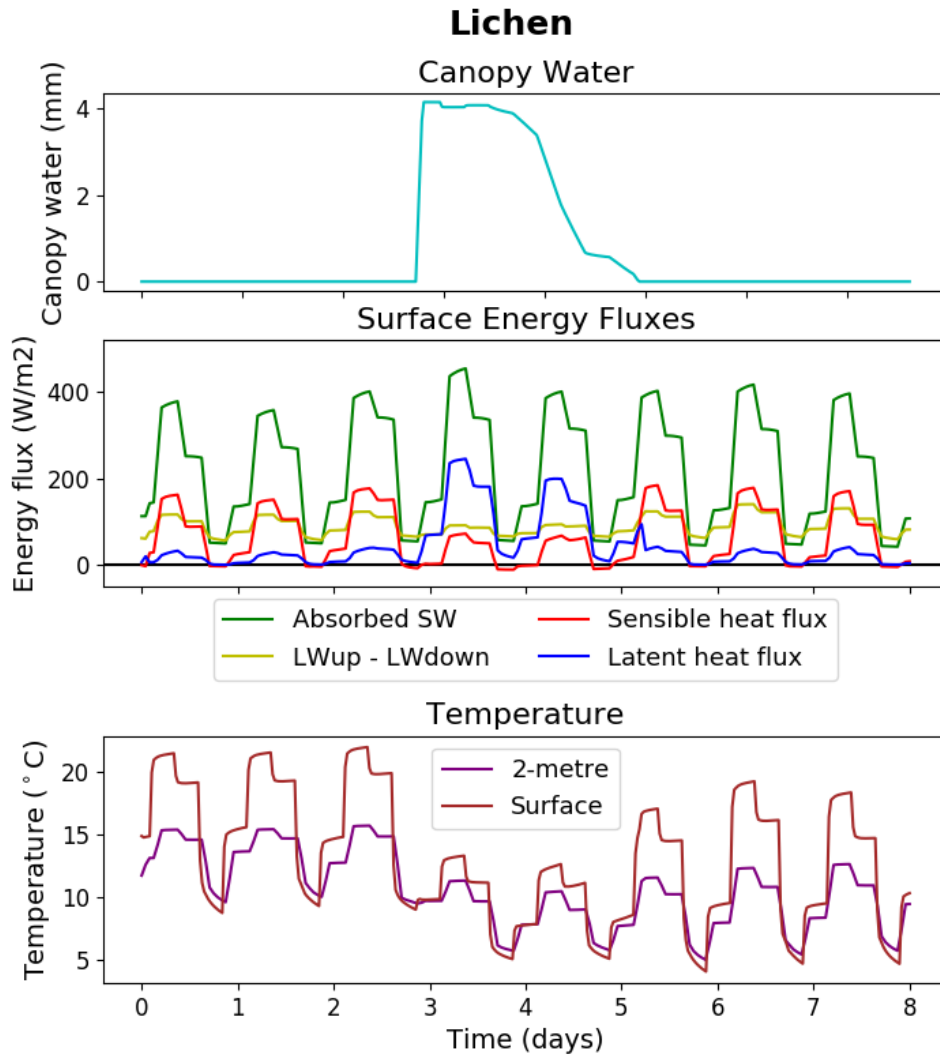


Figure 5.3: Canopy water, surface energy fluxes and temperatures for lichen. Showing hourly output from 1. to 8. of July 2008, with an added rainfall on day four (between number 3 and 4).

differences in absorbed SW from day to day due to changing cloud cover. For the turbulent fluxes, the flux of latent heat is quite small as long as the vegetation is dry but becomes the second largest flux when wet. Correspondingly, the sensible heat flux is much more important than the latent heat when dry but decreases significantly when the vegetation is wet. The surface temperature is warmer than the 2-metre temperature during the day and around the same during the night. While the lichen is wet, the difference between the two temperatures decreases.

How these temperatures should be interpreted is addressed in the discussion on page 50.

Figure 5.4 shows the same two top panels as above, canopy water and surface energy fluxes, for shrubs, but also includes the difference between lichen and shrubs in surface energy fluxes (panel three) and temperatures (panel four).

Here the canopy water dries much faster, and even dries during the rain event. Shrubs are also further from reaching the maximum allowed canopy water, and this is much smaller than for lichen (see section 4.4). For the surface energy fluxes, the largest differences are seen in the latent heat flux. The difference in the sensible heat flux has the opposite sign of the latent heat flux but generally with a smaller magnitude. Otherwise, the absorbed SW is smaller for lichen than for shrubs, while net LW is larger for lichen than for shrub. While dry, the surface temperature is up to 3.5°C warmer for lichen than shrubs, but the 2-metre temperature is only 0.2°C warmer. While the temperatures are larger for shrubs than lichen, the maximum difference is 1.6°C for surface temperature and 1.1°C for 2-metre temperature.

Next, figure 5.5 shows the same four panels for grass, which is parameterised quite similarly to shrubs. It has the same height, aerodynamic parameters, hydrologic parameters and very similar leaf and stem area indices. The root distribution and optical parameters are different however (See table 8.3 in Keith W. Oleson (2013) for root distribution parameters and table 4.1 for the optical parameters).

As expected when the PFTs are so similar, there are many similarities with shrubs, but also differences. The sensible heat flux for grass is smaller than for both lichen and shrubs, while the latent heat flux is larger for grass than both lichen and shrubs. The absorbed SW is smaller for lichen than for grass, and the net LW is about the same for grass as for shrubs. The differences in temperatures are also quite similar to the differences between lichen and shrubs, reaching a difference of 4.1°C for surface and 0.3°C for 2-metre temperature while dry. While lichen is wet, the differences reach 1.1°C for the surface temperature and 0.5°C for the 2-metre temperature.

In addition to shrubs and grass, it is of interest to compare lichen with bare ground. This is shown in figure 5.6, with soil colour 10. The results for bare ground will of course depend on the soil colour (see section 4.3). Number 10 is chosen here because it is in the middle between the lightest and the darkest soil.

Both absorbed SW and net LW is larger for lichen than bare ground. The latent heat flux is more than 100 W/m^2 smaller for lichen than bare ground as long

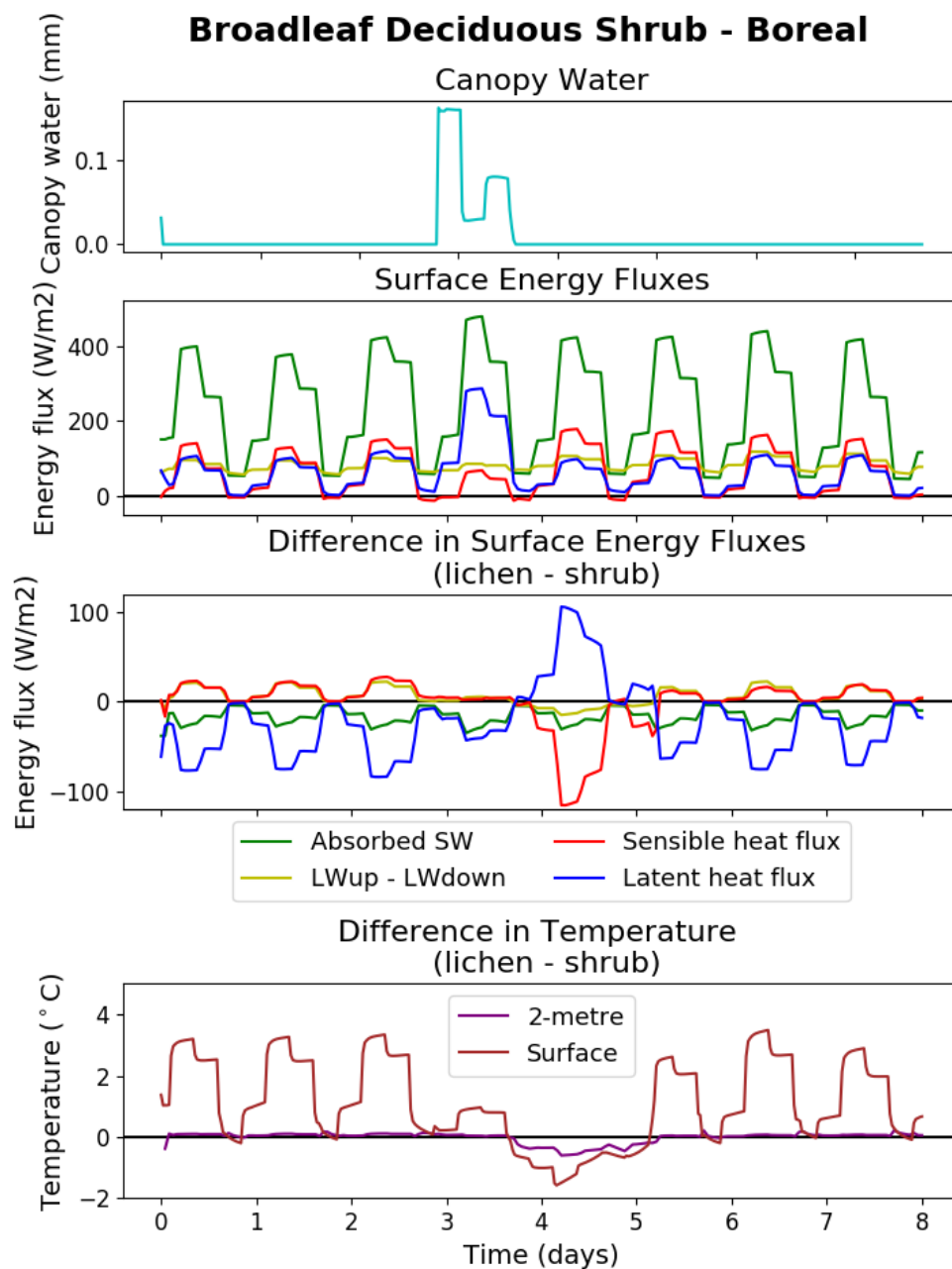


Figure 5.4: Canopy water, surface energy fluxes and difference in surface energy fluxes and temperatures for broadleaf deciduous boreal shrub compared to lichen. The output is from the same period as figure 5.3 with the same added rainfall and the same output frequency. Note that the scale for canopy water is not the same here.

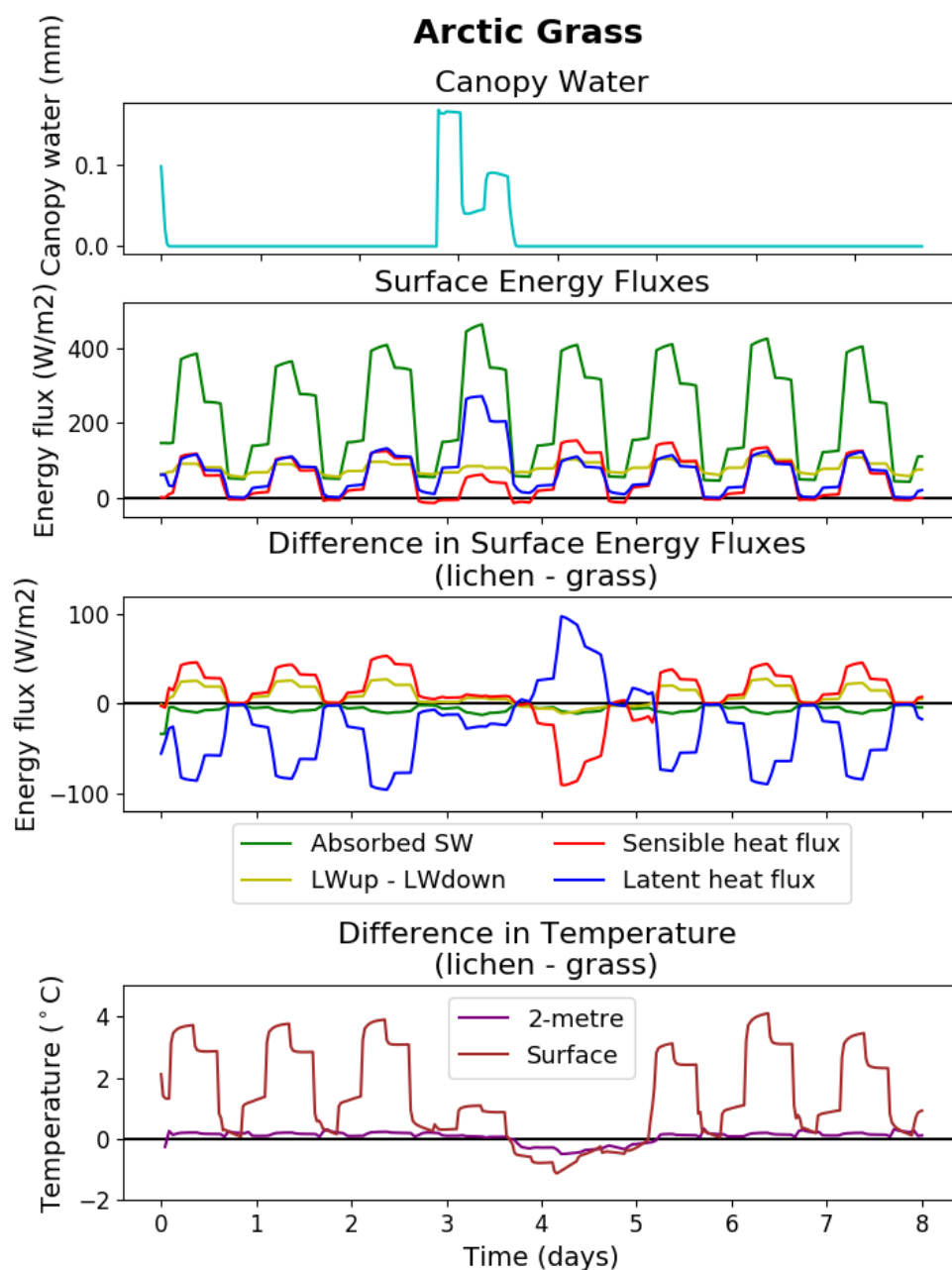


Figure 5.5: Same as figure 5.4 but for arctic grass.

as lichen is dry, and the sensible heat flux around 100 W/m^2 smaller for lichen. When lichen is wet the surface energy fluxes become quite similar for both PFTs. While dry the 2-metre temperature is around 0.5°C warmer for lichen than bare ground, while the surface temperature reaches 3.8°C difference. When wet, the

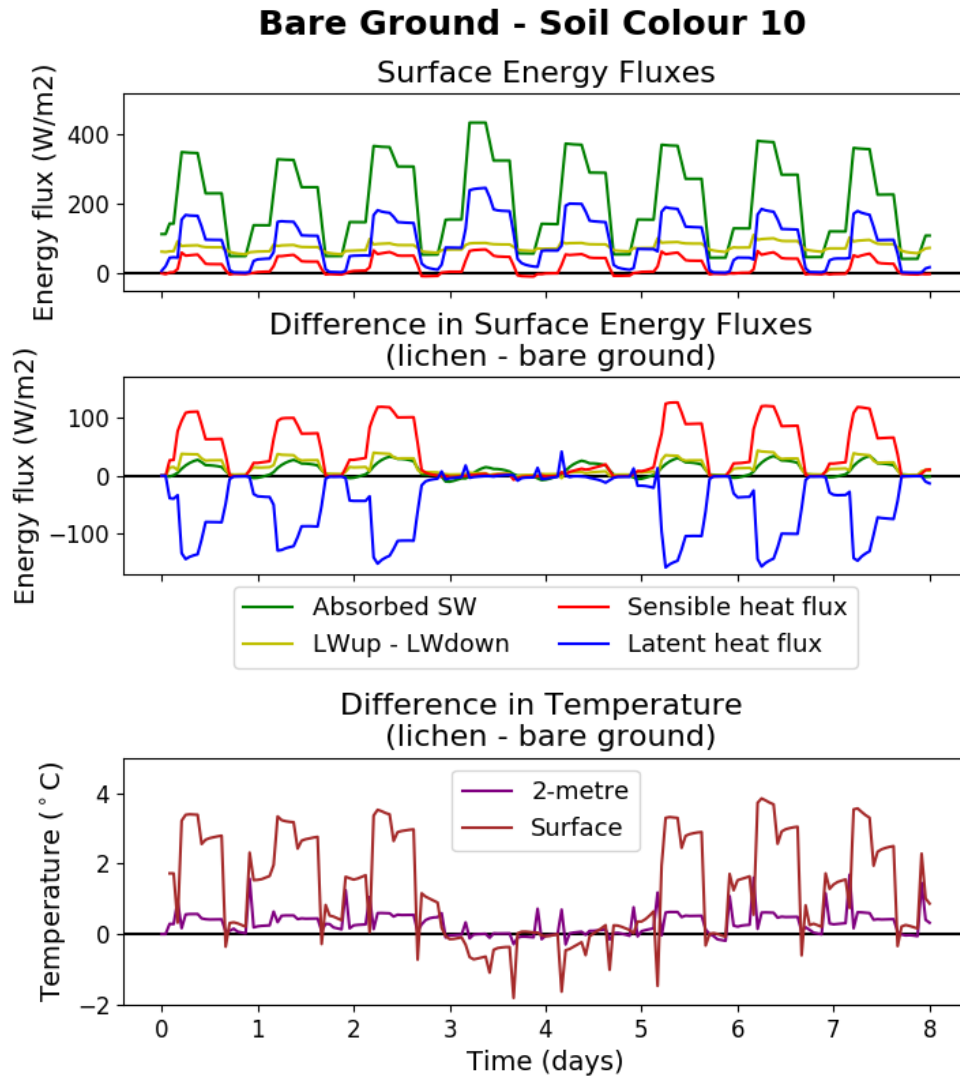


Figure 5.6: Surface energy fluxes and difference in surface energy fluxes and temperatures for bare ground with soil colour 10. The output is from the same period as figure 5.3 with the same added rainfall and the same output frequency. Since bare ground cannot have any canopy water, this is not included. Note that the range on the y-axis for difference in surface energy fluxes is not the same as for shrubs and grass.

2-metre temperature has almost no difference while the surface temperature is around 1°C warmer for bare ground than for lichen.

Discussion

Canopy Water

The maximum canopy water for lichen is more than 15 times that for shrubs and grass and we see this in the results. But while lichen almost reaches the maximum canopy water (reaching 4.15 mm when max is 4.2 mm), shrubs or grass are further from reaching it (reaches 0.16 mm when max is 0.25 mm). The way CLM4.5 calculated evaporation, we will have evaporation from the vegetation as long as the specific humidity of the air is smaller than the saturation specific humidity at the vegetation temperature (see equation 3.4). The vegetation temperature for the model run is higher than the atmospheric forcing temperature for the entire period (not shown), ensuring that this condition true and thus explaining why the canopy water does not reach the maximum.

If we take a look at the latent heat flux the first six hours of the rainfall, it is around 90 W/m² for shrubs, while the rainfall rate is 3.6 mm/h. Using that the latent heat of evaporation is $2.3 \cdot 10^6$ J/kg for water we get that

$$\frac{90 \text{ W/m}^2}{2.3 \cdot 10^6 \text{ J/kg}} = 3.9 \cdot 10^{-5} \text{ mm/s} = 0.14 \text{ mm/h} \quad (5.1)$$

So 0.14 mm of the water evaporates every hour. This is about half of the maximum canopy water, but some of it evaporates from the ground. The same is true for the lichen canopy. However, the latent heat flux is somewhat smaller and also more of the precipitation is intercepted by lichen than by shrubs (see alpha parameter in section 4.4), which explains why the lichen canopy water is closer to the maximum canopy water than shrubs are.

It is important to note that these are idealised cases, and that adding and removing precipitation makes for some unnatural atmospheric forcing as it might not be cloudy at the entire period of the precipitation event. However, the beginning of the rain added here is put at a time with a small amount of precipitation in the original forcing. This is followed by a period of almost no precipitation.

The larger canopy water in lichen explains why drying up the canopy takes longer than for the other PFTs. However, the current parameterisation might not be the best representation of evaporation from lichen. In nature the top of lichens dries quickly, while the bottom stays wet much longer. A more detailed discussion of how this could be better represented in CLM4.5 is given in section 5.5.

Absorbed SW

The differences between the various PFTs depend on the albedo (the incoming solar radiation is the same in all the model runs), which is determined from the

reflectance and transmittance (see section 4.3). Among the vegetated simulations, lichen absorbs the least SW, followed by grass and shrubs, corresponding with the albedos, which are highest for lichen and lowest for shrubs. The lower albedo of lichen than other vegetation is also consistent with what have been found in previous studies (e.g. Cohen et al., 2013; Stoy et al., 2012). The differences in absorbed SW are perhaps smaller than we would have expected due to the light colour of lichen compared to shrubs/grass. However, from figure 4.1 we know that lichen have a lower reflectance than vascular plants in the near infrared part of the spectrum, and the parameters in CLM4.5 is set to reflect this.

The smaller amount of absorbed SW for bare ground than for lichen reflects a higher albedo of soil colour 10 compared to lichen, which may also seem unexpected. However, the soil colour chosen will play a part and soil colour 10 should be somewhere in the middle of the range of colours. The explanation for the higher albedo for bare ground is the same as above, and can be better understood by looking at the reflectances for lichen and bare ground, as shown in figure 5.7. On average there is not much difference between the visible part of reflectances. In the near infrared part, on the other hand, the reflectance for bare ground is clearly higher. This explains why bare ground can have higher albedo even though it might not look lighter than lichen.

Net LW

The net LW is a result of the temperature and the emissivity ϵ (see equation 2.2). Because lichen, shrub and grass all have $LAI + SAI = 2.5$ in July they have $\epsilon_v = 0.92$ (see equation 3.2), and the difference in net LW must therefore come from difference in temperature. Bare ground has a higher emissivity, $\epsilon_{soi} = 0.96$ (see subsection 3.1.2) and when comparing lichen to bare ground the emissivity must therefore be taken into consideration. However, from the results we know that the net LW is smaller for bare ground than for lichen. Since bare ground has larger emissivity, the smaller net LW must be a result of lower temperature, which we can indeed see from the temperature difference plot in figure 5.6.

Sensible Heat Flux

Sensible heat is partly connected to latent heat: if most of the energy goes into latent heat there will not be much left for sensible heat. This is seen in the results, where the sensible heat flux becomes notably smaller when latent heat flux increases. From section 2.1 and equation 3.3 it is known that many variables play a part, but lichen, shrub and grass have the same $LAI + SAI$ and the same aerodynamic parameters. The height is lower for lichen though, which we in the sensitivity tests found to give smaller turbulent fluxes. However, since the sensible heat flux is larger for lichen than shrubs and grass when dry,

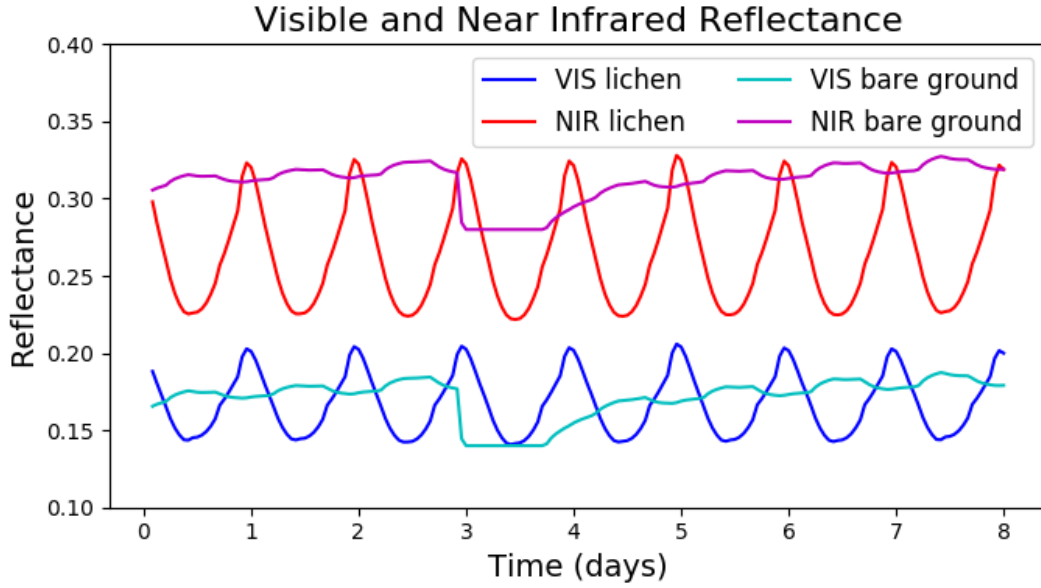


Figure 5.7: Reflectance in the visible and the near infrared part of the spectrum for lichen and bare ground, the same eight days as the other plots in this section. For vegetation, the reflectance varies with the angle of incoming radiation as explained in section 4.3, decreasing with increasing angle. The ground varies depending on the saturation of the surface.

the temperature must be more important. The relatively low sensible heat flux for bare ground is explained by the large latent heat flux, and also connected to the temperature. However, the latent heat flux here is probably too large (see the discussion of latent heat flux under), leading to a too small sensible heat flux.

Latent Heat Flux

In order to have a positive (upwards) latent heat flux there must be available water at the surface. The latent heat flux is therefore depending on whether or not there is water in the canopy, as well as available surface or soil water, which in the model is tied to the specific humidities as seen in equation 3.4. For all the PFTs, excluding bare ground, the latent heat flux is therefore much larger when the canopy contains water than when it does not.

Since lichen contains more water, and therefore takes longer to dry, the latent heat flux is larger for a longer time. It is, however, smaller than for shrubs and grass when there is no canopy water. This is because I have removed transpiration from lichen (see section 4.1). While dry, the latent heat flux from lichen

comes from ground evaporation, while shrubs and grass have an additional source from transpiration. This introduces an interesting question: *What is most important, lichen's lack of transpiration or the larger maximum canopy water for lichen? Over an average month or year, will the large canopy water capacity of lichen or the fact that shrub and grass transpire give the largest latent heat flux?* This question is taken up in section 5.3.

The bare ground has much larger latent heat flux than lichen, except when lichen is wet. This can be explained by available water from the soil, and the fact that water in the model evaporates easier from the ground when there is not any vegetation. The soil thickness in CLM 4.5 is 3.8 metres everywhere (Keith W. Oleson, 2013), which is generally too thick for the areas where lichens grow (Smith et al., 2015). This means that the amount of water in the soil, which is limited by the available pore volume, will be much more than we normally would find where lichen grows, and it follows that the latent heat flux becomes too large. CLM5.0, which have variable soil depth, would probably handle this better (see section 5.6).

Temperatures

When interpreting the temperatures from the results it is important to keep in mind that both the surface and the 2-metre temperature depend on the air temperature from the atmospheric forcing. The 2-metre temperature is more dependent on the atmospheric forcing data than the surface temperature (see subsection 3.1.2), while the surface temperature is more closely connected to the surface fluxes (through its dependence on T_v and T_g). Since the model runs in this thesis were performed offline, the atmospheric forcing was not influenced by changes in the surface energy fluxes. This means that the any differences in temperature between various PFTs are only due to differences in surface energy fluxes, and potentially in the aerodynamic parameters and the vegetation height. Important feedback mechanisms are therefore excluded.

The most important flux for heating the surface is the SW, while the other fluxes mostly are positive and thus works to cool the surface. The temperatures are a result of a combination of all the fluxes (see subsection 3.1.2), and the fluxes, except absorbed SW, a consequence of the temperatures. Lichen have higher temperatures than both shrubs and grass while the vegetation is dry. From the plots of surface energy fluxes we know that lichen absorbs less SW, implying lower temperatures, but the latent heat flux is also much smaller, explaining why the temperatures are higher. While both PFTs are wet, the differences are small in surface energy fluxes, and therefore also in temperatures. But while lichen is wet, and shrubs/grass dry, the much larger latent heat flux results in lower temperatures for lichen.

Since the surface temperature is more directly linked to the surface energy fluxes and less affected by the atmospheric forcing data, the daily variations and the differences between PFTs are larger for this than for the 2-metre temperature. Interestingly, the differences in the 2-metre temperature between lichen and shrubs/grass is larger when lichen is wet than when dry, while the opposite is true for the surface temperature. This could be due to the lower height of lichen which influences the roughness length used to calculate the 2-metre temperature (equation 3.9), but I would need more testing of the temperatures to properly explain this effect.

For bare ground the temperatures are lower than for lichen while lichen is dry, and about the same when it is wet. While lichen is wet the differences in surface energy fluxes are close to zero, explaining the lack of temperature differences. While lichen is dry, there are larger temperature differences than when compared to shrubs or grass as a result of both a larger latent heat flux for the ground and less absorbed SW. However, since the latent heat flux is unrealistically high for bare ground, the temperature difference is might be smaller than what we get here.

As mentioned, Stoy et al. (2012) found a significantly higher nighttime temperature for areas with more lichen (Norwegian side of the border) than with less (Finnish side), but no significant difference during the day. This is the opposite of what was found here, with the differences in temperature found during the day and almost no difference during the night due to small differences in surface energy fluxes. However, Stoy et al. (2012) looked at temperatures over several years and not only during summer. Also, they explained the higher temperature for lichen by its insulating effect, while the higher temperatures from CLM4.5 is clearly the result of the lower latent heat flux. The ground heat flux have been reviewed in more detail in section 5.3 on page 61.

5.3 Seasonal Signals

Motivation

The same idealised single cell experiment has been used to quantify how the surface energy fluxes vary through the year. What was found to be important for the first week of July 2008 might not be important over the entire year or even during an average summer. I therefore want to look at averages over several years to make sure that the results in the previous section are not the consequence of some specific conditions. This way I include realistic precipitation amounts and

frequency, making it possible to answer the question posed above about what is most important of canopy water capacity or transpiration.

From this experiment I want to find out at what time of the year the PFTs are important for the surface energy fluxes and temperature. Secondly, I want to find out how snow cover differs between PFTs and how this affects the surface energy fluxes. Lastly, I want to quantify the effect differences in surface energy fluxes have on the temperature through the year.

Setup

This was done by running 30 years with daily output for the same grid column and PFTs as above. The 30-year period used was 1981-2010, with the CRUNCEP data used as the atmospheric forcing (see subsection 3.1.3) without any modifications. For the surface energy fluxes and temperature the average and the standard deviation for each month was calculated. Since the snow cover fractions are far from having Gaussian distributions, the average and the 25, 50 and 75 percentiles were calculated for each month to better represent how snow cover might differ. The results are plotted and presented under.

In this section, only the 2-metre temperature is included even though the surface temperature is less affected by the atmospheric forcing data. This is because I do not get the surface temperature directly out of the model. In section 5.2 I printed the temperature as it was calculated, which is only viable for single column and a short time period. With more time, the surface temperature could of course have been included in the output.

Results

Figure 5.8 shows how the average snow cover, surface energy fluxes and 2-metre temperature are each month for lichen. The plot of snow cover is presented in a box diagram and the surface energy fluxes and temperature plots includes plus/minus one standard deviation. All the results in this section are discussed from page 59.

The top panel tells us October is the month where the snow cover varies most from year to year. From the middle panel we see that the surface energy fluxes are largest, and have the largest variation (large standard deviation), during

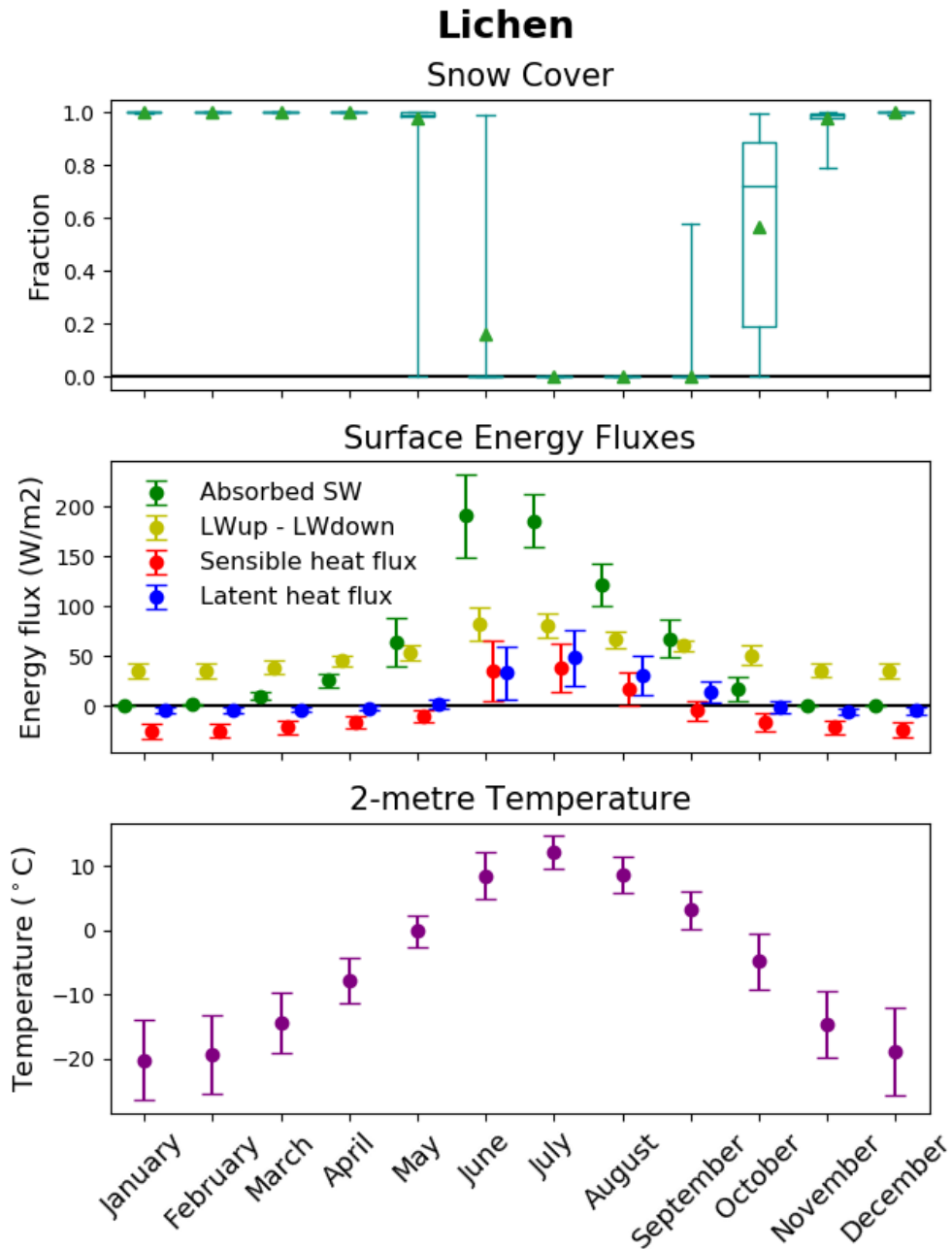


Figure 5.8: Monthly snow cover, surface energy fluxes and 2-metre temperature for lichen. The snow cover is shown as a box diagram. The green triangle shows the mean, while the boxes shows the 25 percentile, the median and the 75 percentile as the three lines of the box. The bars show the full range of the values. For surface energy fluxes and 2-metre temperature the average is indicated by the dot while the error bars show one standard deviation.

summer. For the 2-metre temperature the largest standard deviations are found during the winter.

From these plots for lichen, we can now compare lichen with other PFTs. Figure 5.9 shows the monthly average of difference in snow cover, surface energy fluxes and 2-metre temperature between lichen and shrub presented in the same kinds of plots.

The three months when the average difference in snow cover is not zero is May, June and October, where the average is almost 0.1 higher for lichen than for shrub. For all months except October, both the 25 and the 75 percentile are at the zero line. This means that at least 50 % of the days has no difference in snow cover. For October, where both the 25 and the median are above the zero line, more than 50 % of the days have a larger snow cover fraction for lichen than shrubs. The average amount of absorbed SW has largest difference in late spring and is largest for shrubs. For latent heat flux the difference is largest in summer, peaking in July. Differences in net LW and sensible heat are both positive and negative over the year and less than 5 W/m^2 . The largest average difference in 2-metre temperature is found for the months with average difference in snow cover, where shrubs are warmer than lichen by up to 0.4°C . In the summer, when there is no snow cover, the temperature is 0.05°C warmer on average for lichen than for shrubs.

Figure 5.10 shows the same as figure 5.9 but for grass instead of shrubs. We see that the only month where the average, and the 25 and 27 percentiles, for the difference in snow cover are different from zero is October, where the average snow cover fraction is approximately 0.08 larger for lichen than grass on average. The difference in absorbed SW between lichen and grass is much smaller than between lichen and shrubs. The net LW and sensible heat flux are both larger for lichen than grass, and the latent heat flux is smaller for lichen than for grass. The 2-metre temperature is higher for lichen than grass in summer and opposite in autumn. The average difference is largest in October when the temperature is 0.25°C warmer for grass than lichen.

Figure 5.11 shows the same three panels for bare ground, with soil colour 10, compared to lichen. The averages in snow cover are always on or just below the zero line. The same is true for the 25 and 75 percentiles for all months except October. Unlike shrubs and grass, bare ground absorbs less SW than lichen. The difference in net LW flux is similar to the shortwave, although around 2 W/m^2 smaller. The latent heat flux is around $25\text{-}30 \text{ W/m}^2$ larger for bare ground than lichen in June and July, while the sensible heat flux has about the same difference but is larger for lichen. The largest difference in 2-metre temperature is found

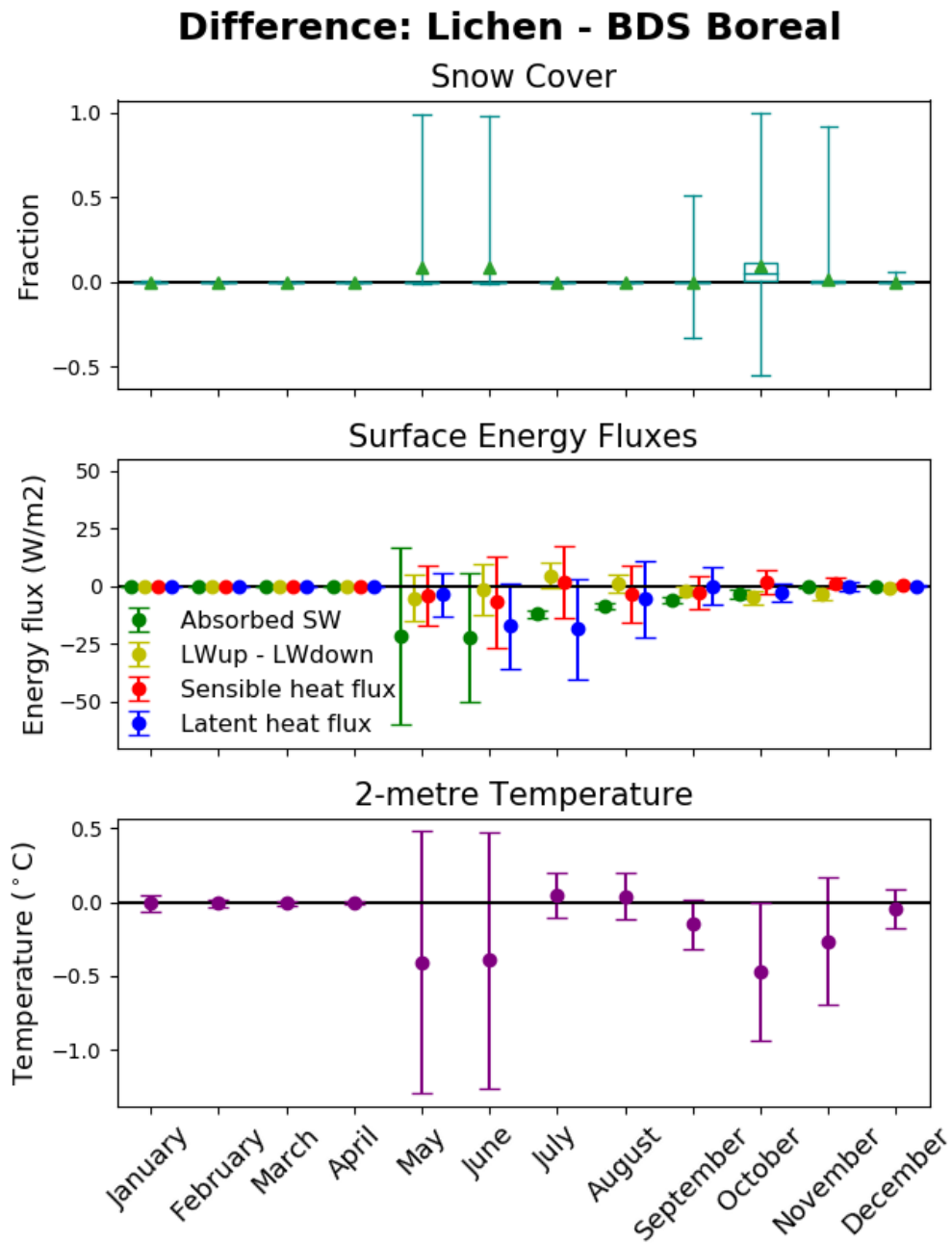


Figure 5.9: Monthly difference in snow cover, surface energy fluxes and 2-metre temperature between lichen and broadleaf deciduous boreal shrub. The panels show the same as figure 5.8 except that these show differences between PFTs.

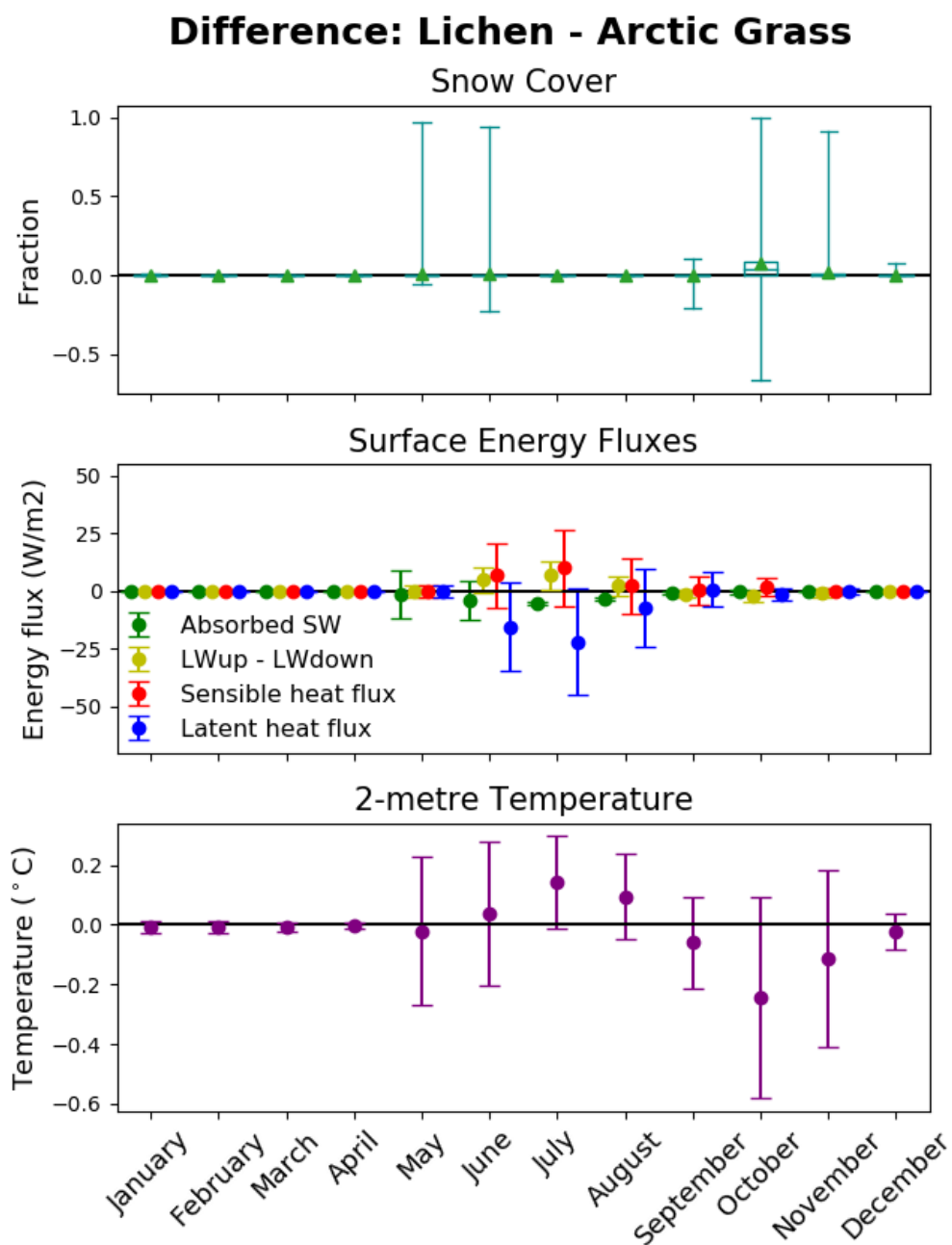


Figure 5.10: Monthly difference in snow cover, surface energy fluxes and 2-metre temperature between lichen and arctic grass. The panels show the same as figure 5.9 for grass.

Difference: Lichen - Bare Ground (Soil Colour 10)

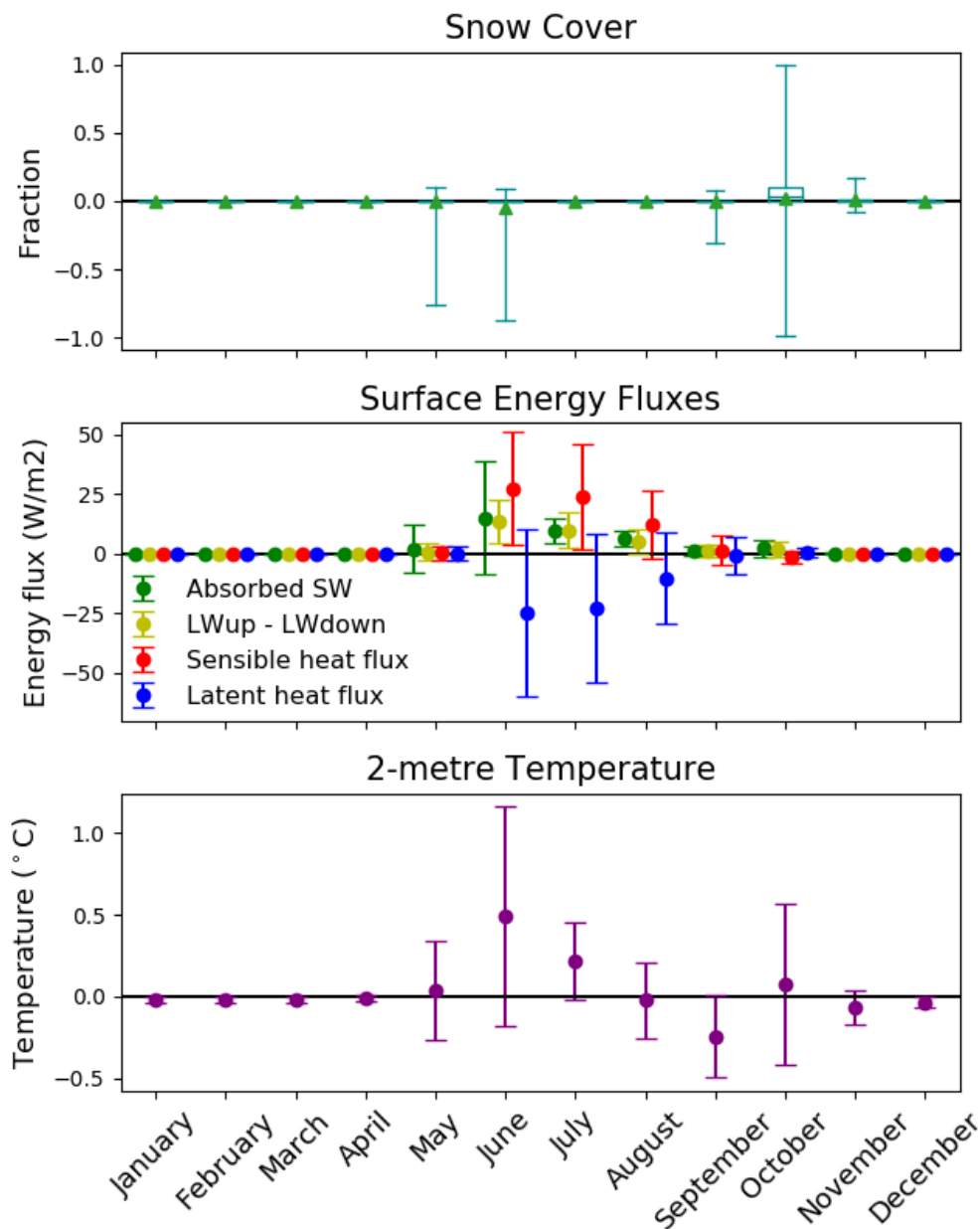


Figure 5.11: Monthly difference in snow cover, surface energy fluxes and 2-metre temperature between lichen and bare ground with soil colour 10. The panels shows the same as figure 5.9.

in June, when the temperature on average is 0.5°C warmer for lichen than for bare ground. September is the month where bare ground is warmest compared to lichen, by an average of 0.25°C .

Figure 5.12 shows the average difference in surface energy fluxes and 2-metre temperature over 30 years between lichen and shrubs, grass and bare ground. As seen in the previous figures, most of the differences in the monthly averages have consistent signs for all months, and consequently the average over the year shows the same here. However, the sign of the net LW and sensible heat flux for the comparison between lichen and shrubs varies from month to month. We see here that on average both are smaller for lichen than shrubs. The 2-metre temperature is close to the same for all PFTs except for shrubs, which is almost 0.2°C warmer than lichen.

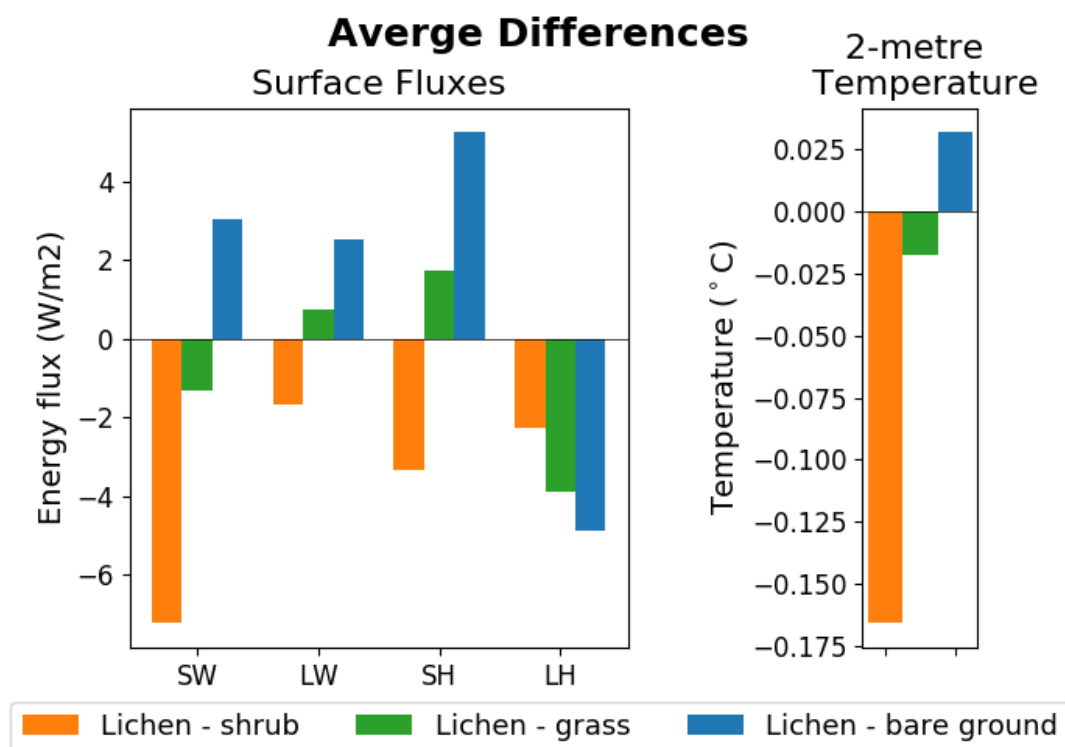


Figure 5.12: 30-year average difference in surface energy fluxes and 2-metre temperature between lichen and shrub, grass and bare ground (1981-2010). Abbreviations: SW - absorbed SW, LW - net LW, SH - sensible heat flux, LH - latent heat flux.

Discussion

Snow Cover

The complete snow cover from January until April explains the lack of difference in surface energy fluxes and temperature in these months. The difference in snow cover is naturally largest in May/June when the snow is melting and in autumn when the snow starts to cover the ground again.

The differences in snow cover between PFTs must be a consequence of differences in the surface energy fluxes, even though the differences are small. As mentioned, the leaf and stem area indices varies through the year (except for lichen) as described in section 4.1 (table B.1 gives an overview of LAI and SAI for shrubs and grass). Additionally, as the vegetation gets buried by snow, the exposed leaf and stem area indices decreases depending on the snow depth and the vegetation height as described in subsection 4.1.2. This means that the removal of transpiration from lichen will be less important as less leaves for grass and shrubs means less transpiration. The exposed LAI and SAI are also important for calculating the albedo, and the radiative transfer in the vegetation as described in subsection 3.1.2 (page 19). And they are important for the turbulent fluxes, which are larger for larger exposed $LAI + SAI$ (equation 3.3 and 3.4). Finally, the exposed $LAI + SAI$ determine the emissivity (see equation 3.2), which will decrease for decreasing $LAI + SAI$. From the model output we cannot identify which of these effects that introduce the differences in snow cover. With the time permitting, more sensitivity tests with focus on snow cover could have been performed to single out which effects that are important.

While CLM4.5 parameterises the snow cover fraction to account for spatial variability as described in Swenson and Lawrence (2012), it probably does not give a realistic snow cover for my study area. Lichens often grow places that are windy, which reduces the snow cover in these areas. In nature, much of the difference in snow cover fraction between lichen and other vegetation is therefore due to where they grow.

Absorbed SW

Most SW is absorbed in June due to this being the month with most incoming solar radiation. This is also the month where the differences between PFTs are largest, due to a combination of a lot of incoming SW and the fact that the snow cover sometimes differs in this month. The surface albedo is calculated separately for snow-free and snow-covered fractions of the grid cells, and additionally the albedo depends on the exposed $LAI + SAI$ which varies as described above. We see that the PFTs with larger average snow cover have less absorbed SW, as expected due to the high albedo of snow. The amount of absorbed SW also

follows the same pattern as seen for the eight days in July (section 5.2), being largest for shrubs (lowest albedo), followed by grass, lichen and bare ground (highest albedo).

Net LW

As mentioned previously, the net LW is a result of temperature and emissivity, and the emissivities varies through the year with the $LAI + SAI$. The snow emissivity $\epsilon_{sno} = 0.97$, and must be taken into account when there is snow on the ground. When the snow cover is complete, both the temperature and emissivity are therefore the same and we get no difference in net LW. The rest of the year the PFT with the highest temperature tends to have the largest net LW, because of the larger importance of temperature compared to emissivity (see equation 2.2).

Sensible Heat Flux

Due to the large latent heat flux for bare ground cooling the surface during the summer, the sensible heat flux is much smaller for bare ground than for lichen. This is the same as seen for the eight days in July. The lower sensible heat for grass compared to lichen can also be explained by the larger latent heat and lower temperatures. Shrubs also have larger latent heat flux than lichen, but due to the larger absorbed SW, the sensible heat flux is larger than for lichen on average.

Latent Heat Flux

For the latent heat flux it was expected that two factors would be important: The much larger maximum canopy water for lichen than for other PFTs and the fact that lichens do not transpire. From the results we see that the latent heat flux is smaller for lichen than the other PFTs for all months, meaning that lichen's lack of transpiration is most important of the two on average. However, this is only the answer for this specific region, and will depend on the local climate (e.i. the precipitation amount and frequency). Bare ground also has larger latent heat flux than lichen, although this is not due to transpiration, but rather that bare ground has a much larger evaporation from the soil which can contain more water than any PFT. However, as mentioned in section 5.2 (on page 49) the evaporation from the ground is unrealistically high.

2-metre Temperature

Of particular interest is of course the 2-metre temperature, since this can tell us how the changes at the ground can affect the atmosphere. The average temperature for the snow-free months is larger for lichen than other PFTs, which fits well with the lower albedo (except compared to bare ground) and the smaller latent heat flux. In spring and autumn the temperature is dependent on the snow

cover, with larger snow cover reflecting more SW and therefore leading to lower temperatures. On average over the whole 30-year period the largest difference is found between lichen and shrub, with shrub being warmer due to the lower albedo. However, for most months, and on average, the 2-metre temperature does not differ much between the PFTs. This is not unexpected, since the 2-metre temperature is also affected by the atmospheric input forcing which does not change and will dampen any effect we might see, as noted in section 5.2.

5.3.1 Ground Heat Flux

As mentioned in the introduction, lichens often work as an insulating layer for the soil (Porada et al., 2016; Stoy et al., 2012). Therefore it is of interest to look at the ground heat flux. Figure 5.13 shows the monthly average of this flux, including standard deviation, for lichen, shrubs, grass and bare ground of soil colour 10.

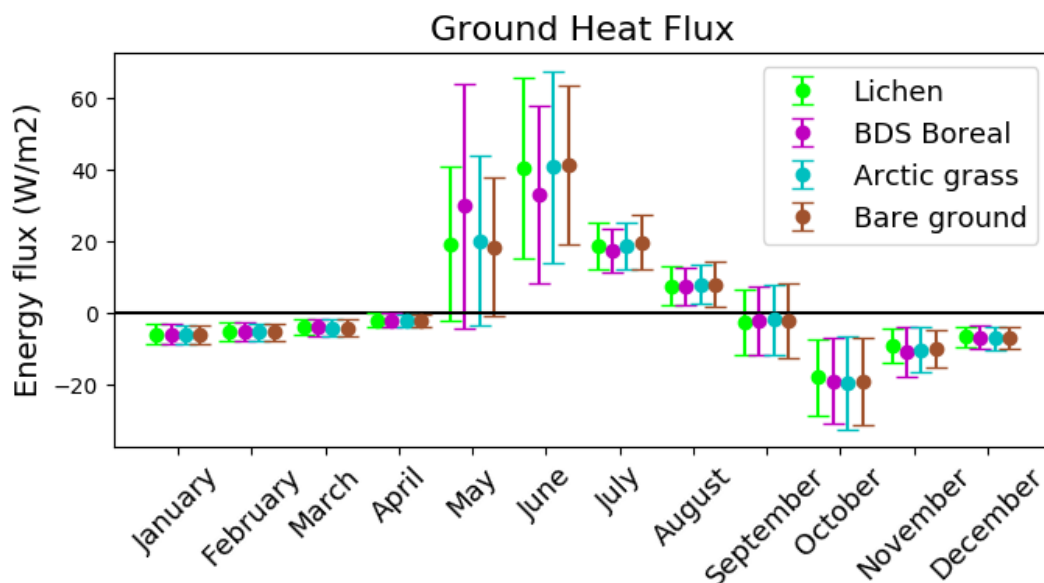


Figure 5.13: Ground heat flux for lichen, broadleaf deciduous boreal shrub, arctic grass and bare ground with soil colour 10. The average is indicated by the dot while the error bars show plus/minus one standard deviation.

As for the other surface energy fluxes, the ground heat flux is the same for all the PFTs while the snow cover is complete, and the largest differences are found in May and June. However, while we would expect lichen to have a

lower ground heat flux than other PFTs, the PFT that stands out is shrub. As mentioned in subsection 3.1.2, CLM4.5 calculates the ground heat flux from the other surface energy fluxes, and the differences in ground heat flux is therefore simply differences in the balance between the fluxes. In May, the shrub cover absorbs more SW than the other PFTs, perhaps because of a feedback between the lower albedo of shrubs and less snow cover, while there is very little difference in the other surface energy fluxes. In June the balance difference is more difficult to discern due to much more differences between PFTs in all the surface energy fluxes.

Based on these result, lichen cover does not have the cooling effect found by Porada et al. (2016). Since CLM4.5 uses the ground heat flux as the boundary condition for heat into the top soil (see subsection 3.1.2), will any insulating effects of the PFTs solely be a consequence of the other fluxes. However, the way CLM4.5 calculates the ground heat flux may not be the best way to do it if we want to capture the insulating effects of lichens. Porada et al. (2016) found that it was important to include the dynamic thermal properties of lichens, which depend on canopy water and on whether the water is liquid or solid, to realistically represent the cooling effect. In CLM4.5 only the thermal conductivity of the soil is included, and we can therefore not expect to see the same effect.

5.4 145x120 km Grid

Motivation

Now that I have seen the importance of lichen cover I want to find how large the effect will be when I use an estimated amount of lichen heath cover in Finnmark from a distribution model. By doing this, each grid cell gets a PFT distribution, such that removal of lichen give more realistic flux changes. This should make it possible to say something about the implications lichen cover might have on the local climate in Finnmark.

Setup

I have looked at a specific area in Finnmark, using a regional run as described in subsection 3.1.3 with a resolution of 20x20 grid cells. The lichen cover used is lichen heath from a distribution model as described in subsection 3.2.1 and showed in figure 3.3. CLM4.5 was run for five years with monthly output, and

monthly and yearly averages were calculated. The years 2006-2010 was used since these are the most recent years I had available. New runs where lichen was replaced by bare ground or shrubs were then performed and compared with the run with lichen. Note that only the lichen part of the areas with lichen heath was replaced, the shrub and bare ground parts of the lichen heath was not changed.

Soil Colour

As mentioned the results will depend on the soil colour as described in section 4.3. Figure 5.14 shows the soil colours for the entire 145x120 km grid. The soil colours are estimated from MODIS observations, to best reproduce local solar noon surface albedo values (Keith W. Oleson, 2013). We see that for this grid, there are mostly lighter colours at the places where we have lichen. For this study, I assume this is correct and use this distribution.

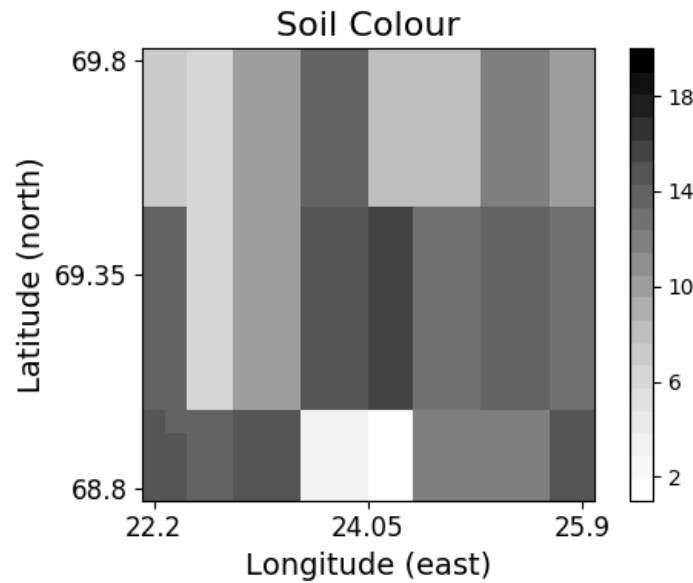


Figure 5.14: Soil colour for the grid used from CLM. The soil colour range from 1 to 20 with 1 being the lightest and 20 the darkest.

Results for July

Again I start by looking at July because this is one of the months where the differences in surface energy fluxes typically are large and there is no snow cover. All the results presented here are discussed on page 69.

Figure 5.15 shows the July average surface energy fluxes for a regional run with estimated lichen heath distribution from distribution modelling (see figure 3.3). We see from the figure that the areas with more lichen absorb less SW and have smaller sensible and latent heat fluxes. This agrees relatively well with the properties that were found for lichen compared to shrubs and grass in previous sections. However, we cannot know if these patterns are due to lichen cover, or if there is a correlation between lichen cover and clouds, but the lack of the same pattern in LW suggests that this is not the case.

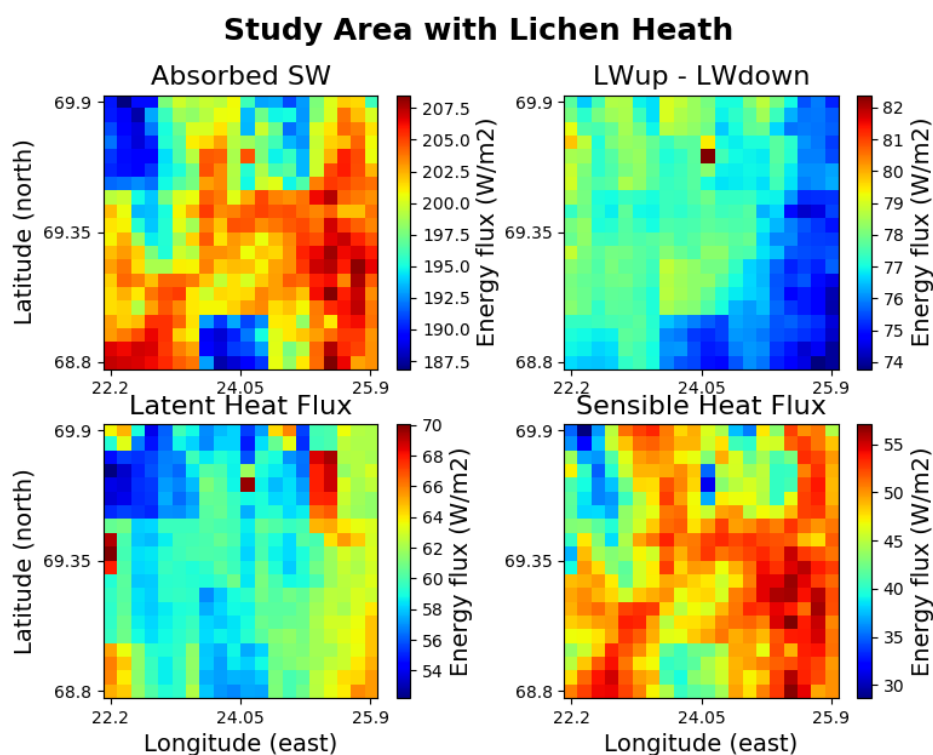


Figure 5.15: Average surface energy fluxes for July for a run with lichen heath from the distribution model. Atmospheric input from July 2006-2010.

The next figure, 5.16, shows the 2-metre temperature for the same area with the same vegetation. We clearly see that some areas are warmer than other.

However, we cannot see any clear indications of the lichen distribution from the temperatures.

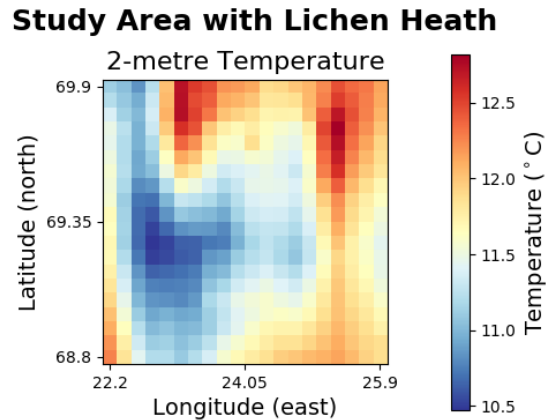


Figure 5.16: Average July 2-metre temperature for a run with lichen heath from the distribution model. Atmospheric input from July 2006-2010.

Figure 5.17 gives an overview of differences in the surface energy fluxes and 2-metre temperature for a regional run with estimated lichen heath distribution and runs where lichen have been replaced by either bare ground or shrubs. The differences are average over both July and the grid. Maximum and minimum July-average differences in the grid are shown by the error bars.

The surface fluxes all have the same average differences as found for July in section 5.3, except for sensible heat between lichen and shrubs. Here sensible heat is larger after shrubs have replaced lichen, while the opposite was found in the previous section. The temperature difference between bare ground and lichen is also of the same sign as what was found previously for July, while the difference between lichen and shrubs is opposite.

The averages, and maximum and minimum, differences gives a good overview of the surface energy fluxes and 2-metre temperature and how these vary between PFTs. However, how these differences are distributed in the grid is also of interest. A more detailed look at the differences in the grid is therefore shown in the following figures.

Figure 5.18 shows the differences in the surface energy fluxes between the case with lichen heath and a case where all lichen has been replaced by bare ground. We clearly see that the differences appear where the vegetation cover differs between the two runs.

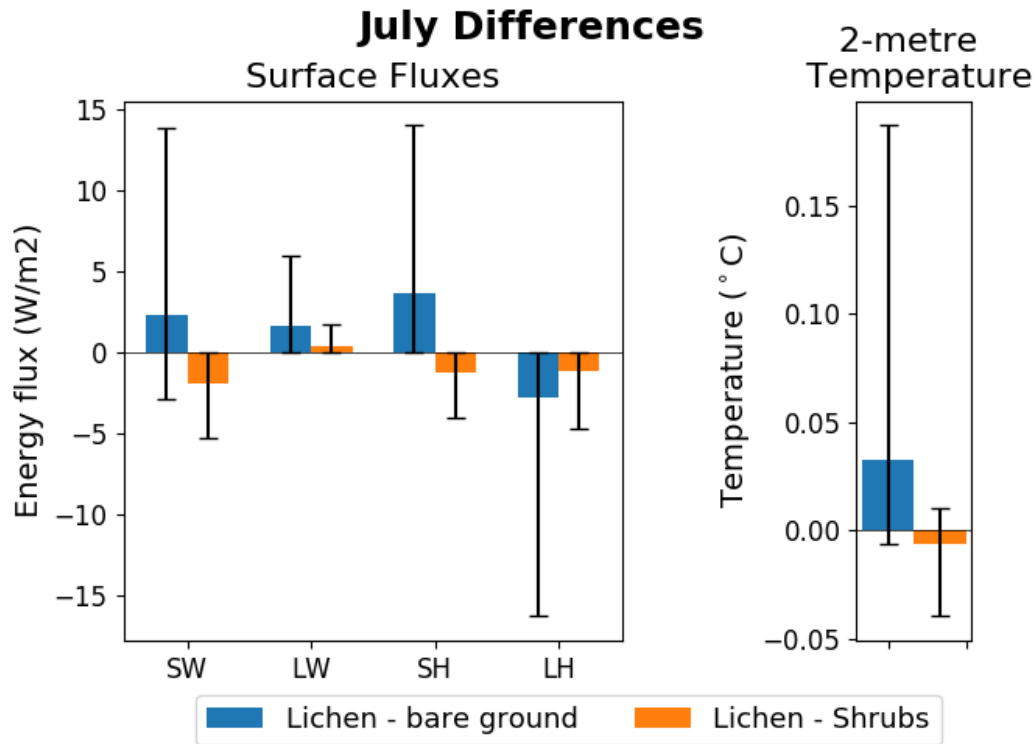


Figure 5.17: Bar chart showing the difference in surface energy fluxes and 2-metre temperature averaged over July and the grid, between a run with lichen heath and runs where lichen have been replaced by either bare ground or shrubs. The error bars indicate the July average maximum and minimum differences between the PFTs found in the grid. Atmospheric input from July 2006-2010.

Figure 5.19 shows the difference in the 2-metre temperature corresponding to figure 5.18. Also here the differences are clearly where lichen has been removed, being higher with lichen than when it have been removed.

The next figure, 5.20, shows the same as figure 5.18 but with lichen replaced by shrubs instead of bare ground. Again the differences mainly appear the placed where lichen has been.

Figure 5.21 shows the 2-metre temperature differences for the same comparison as figure 5.20. As illustrated in the bar chart (figure 5.17), the differences are very small, and the temperature was lower before lichen had been replaced by shrubs.

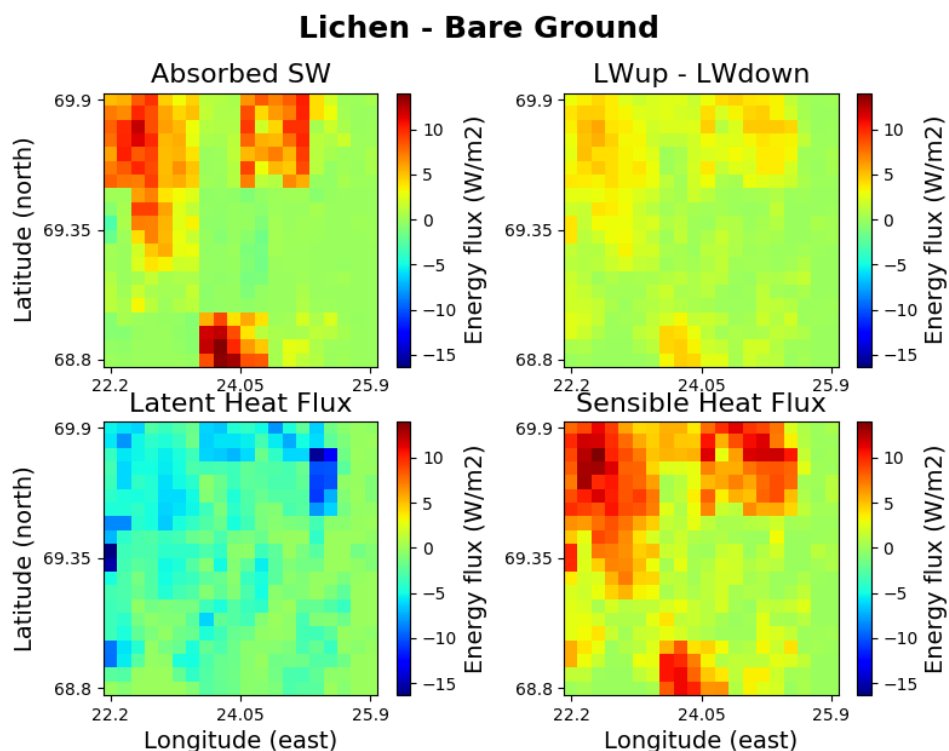


Figure 5.18: Difference in average July surface energy fluxes between a run with lichen heath and one where the lichen is replaced by bare ground. The averages were calculated for July over five years, 2006-2010.

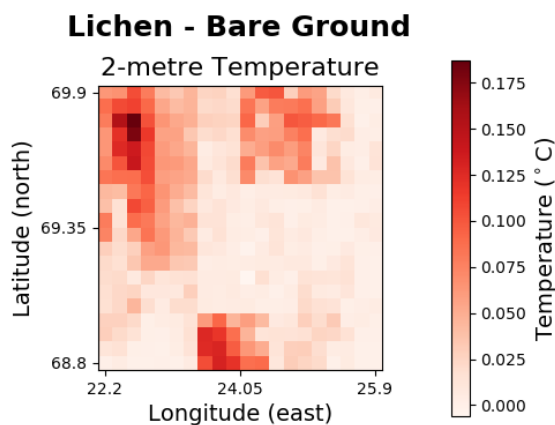


Figure 5.19: Difference in average July 2-metre temperature between a run with lichen heath and one where the lichen is replaced by bare ground. The average was calculated for July over five years, 2006-2010.

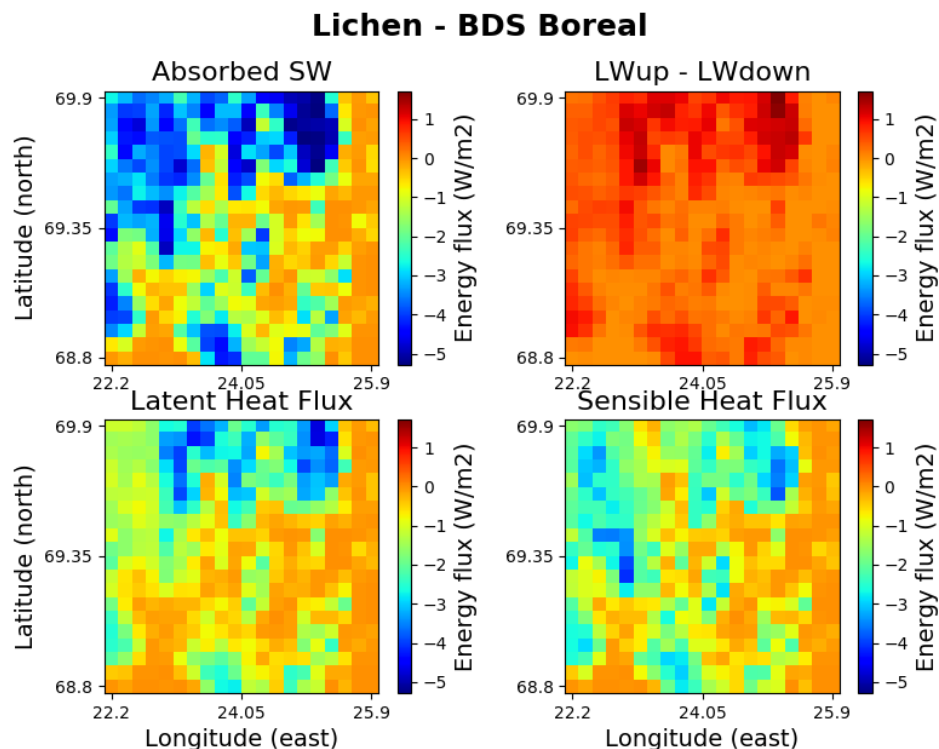


Figure 5.20: Difference in average July surface energy fluxes between a run with lichen heath and one where the lichen is replaced by broadleaf deciduous boreal shrub. The averages were calculated for July over five years, 2006-2010.

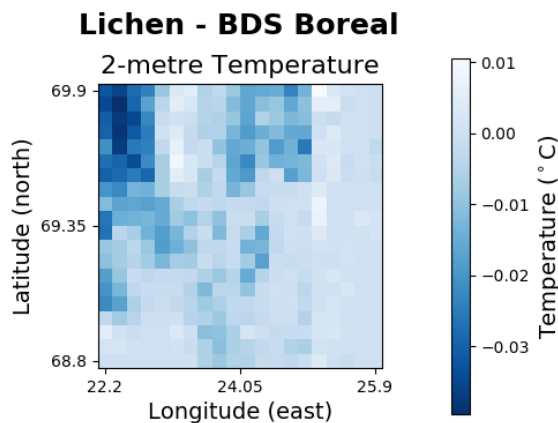


Figure 5.21: Difference in average July 2-metre temperature between a run with lichen heath and one where the lichen is replaced by broadleaf deciduous boreal shrub. The average was calculated for July over five years, 2006-2010.

Discussion for July

Generally the regional cases agree relatively well with the properties that were found for lichen compared to shrubs and bare ground in the previous sections for July. The different albedos between the PFTs explain the differences in absorbed SW. Higher net LW for lichen than both bare ground and shrubs is the same as found in section 5.3, but here the lower value for shrubs is not reflected in an averagely lower 2-metre temperature. However, since the emissivity is the same for shrub and lichen in July the lower net LW must mean that the surface temperature is lower even if the 2-metre temperature is higher. This could be due to the two temperatures' different dependence on the air temperature from the atmospheric forcing, the aerodynamic parameters and vegetation height. The sensible heat flux differ as previously found when lichen is replaced by bare ground, but not when replace by shrubs. This is probably an effect of the years chosen here, that the average over 2006-2010 will not be the same as the average over 1981-2010. The smaller latent heat flux with lichen than without in both cases is in line with the previous sections, but again it must be stressed that the latent heat flux is unrealistically high for bare ground (see page 49).

For the case where lichen is replaced by bare ground the temperature is higher with lichen than without, which was also the case when the vegetation was dry as seen in section 5.2 and the result of the July average in section 5.3. Again it can be explained by the higher albedo and latent heat flux of bare ground compared to lichen. The indication of lower temperatures with lichen than when replaced by shrubs is the opposite of what was found in the previous section for July alone, but the same as found for the yearly average. However, the differences are very small both here and for the July average in the previous section. This means that, like for the sensible heat flux, the years used are important for the results.

Results for Yearly Average

Figure 5.22 shows the yearly average surface energy fluxes for the study area with lichen heath. The magnitude of the fluxes is considerably smaller than they are for the July average and the areas with lichen mostly have smaller surface energy fluxes than the areas without. The discussion of these results can be found on page 75.

In figure 5.23 we see the average 2-metre temperature for the same grid box. The plot looks very much the same as figure 5.19, but with lower temperatures.

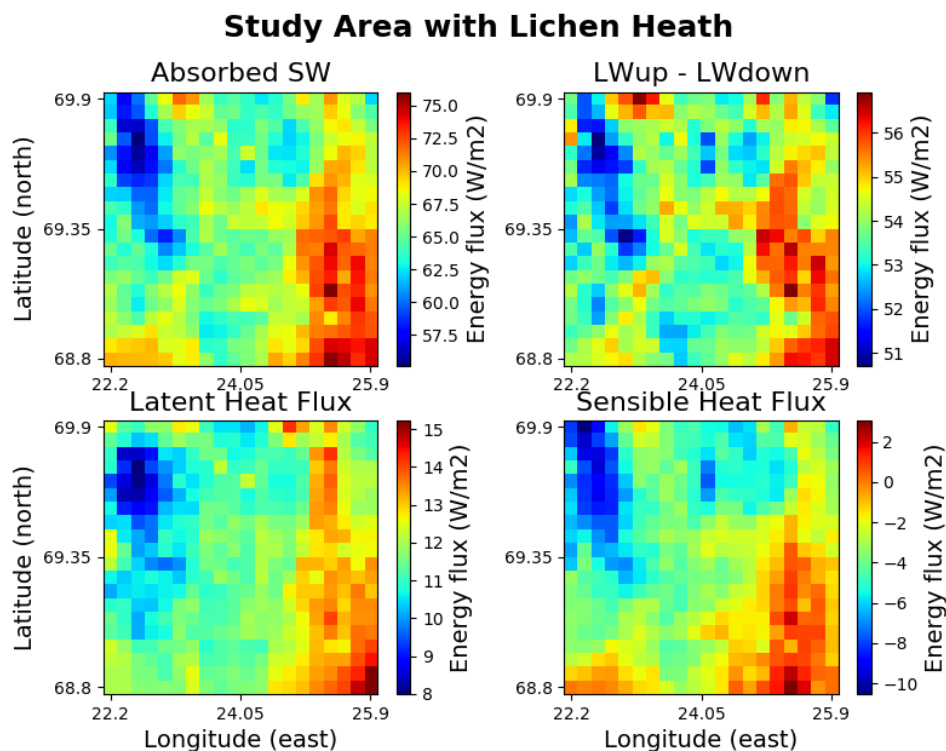


Figure 5.22: Average surface energy fluxes for a run with lichen heath from the distribution model. The averages were calculated for 2006-2010. Note that the range of energy fluxes are different between the panels.

Figure 5.24 shows the average differences in surface energy fluxes and temperature between the model run with lichen, as shown in figure 5.22, and runs where lichen have been replaced by either bare ground or shrubs. The differences have the same signs as for July, except for net LW between lichen and shrub, and also the same signs as what was found for the yearly average in section 5.3. As above, more detailed figures showing the entire grid follows.

Figure 5.25 displays the annual average difference in surface energy fluxes between a run with estimated lichen heath and one where lichen has been replaced by bare ground. The figure is very similar to figure 5.18, but the differences are smaller than for July alone.

The 2-metre temperature for the same case, presented in figure 5.26, shows that the temperature differences are found the places where the vegetation cover differ between the two runs, being higher with lichen than when lichen have been removed.

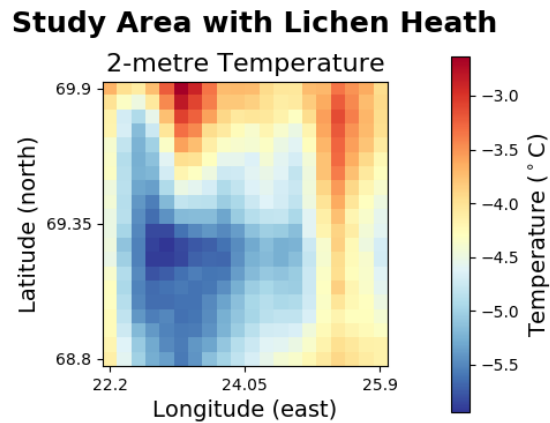


Figure 5.23: Average 2-metre temperature for a run with lichen heath from the distribution model. The average was calculated for 2006-2010.

Figure 5.27 displays the same as figure 5.25, but here lichen is replaced by shrubs. As for bare ground, the figure looks very similar to the equivalent figure for the July average but with smaller differences for all fluxes. The only exception is the net LW, which here is lower with lichen than without as seen in the bar chart (figure 5.24).

Figure 5.28 shows the 2-metre temperature difference corresponding to figure 5.27. The temperature differences are also here found where the vegetation cover differs between the runs.

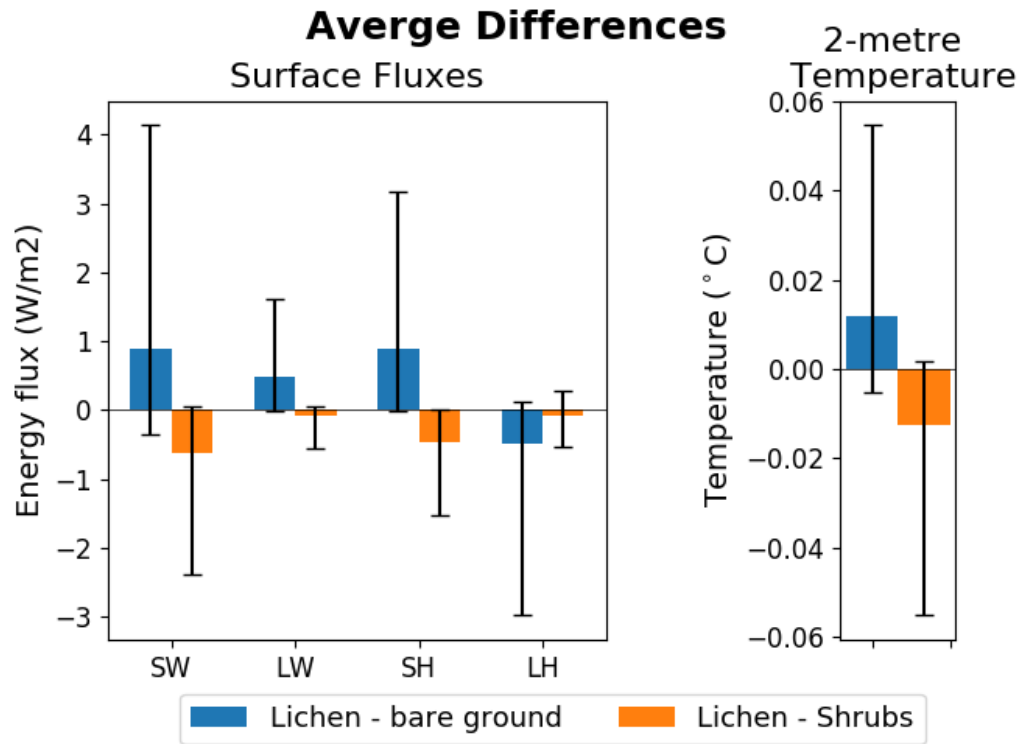


Figure 5.24: Bar chart showing the difference in surface energy fluxes and 2-metre temperature averaged over time and space, between a run with lichen heath and runs where lichen have been replaced by either bare ground or shrubs. The error bars indicate the time average maximum and minimum differences between the PFTs found in the grid. The averages are calculated over 2006-2010.

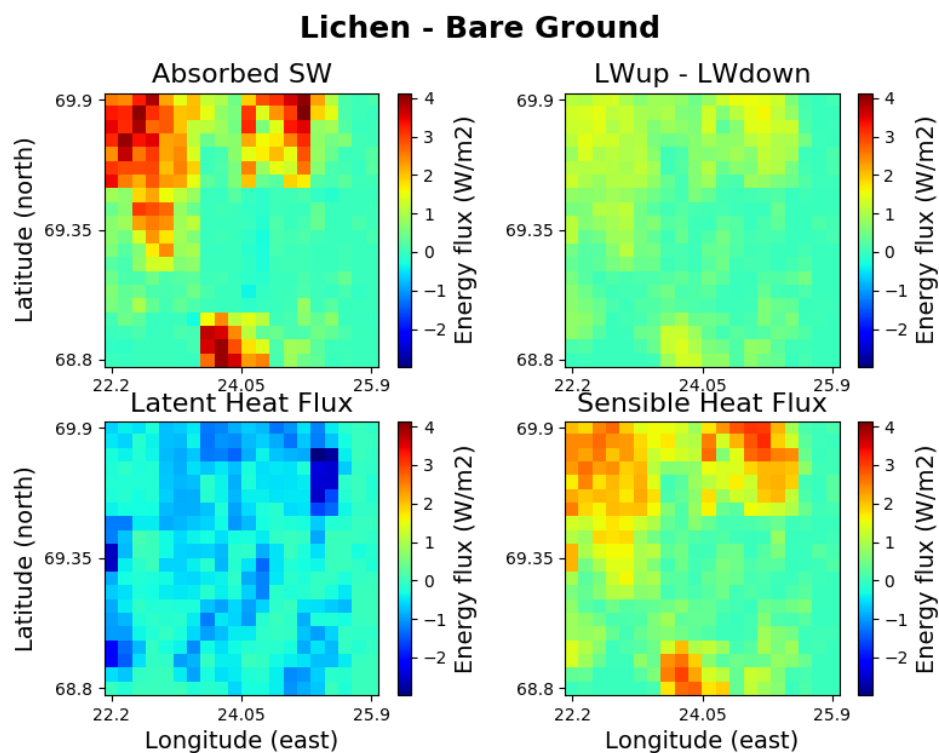


Figure 5.25: Average difference in surface energy fluxes between a run with lichen heath and one where the lichen is replaced by bare ground. The averages were calculated for 2006-2010.

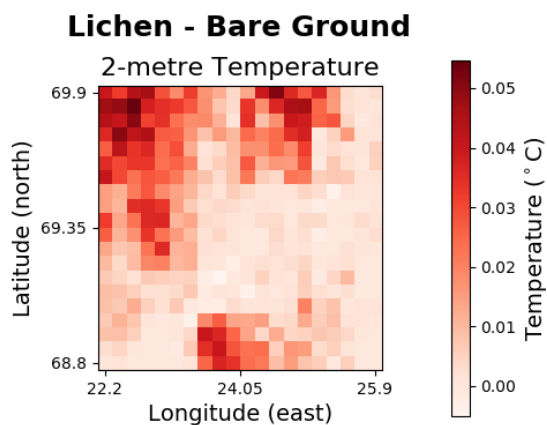


Figure 5.26: Average difference in 2-metre temperature between a run with lichen heath and one where the lichen is replaced by bare ground. The average was calculated for 2006-2010.

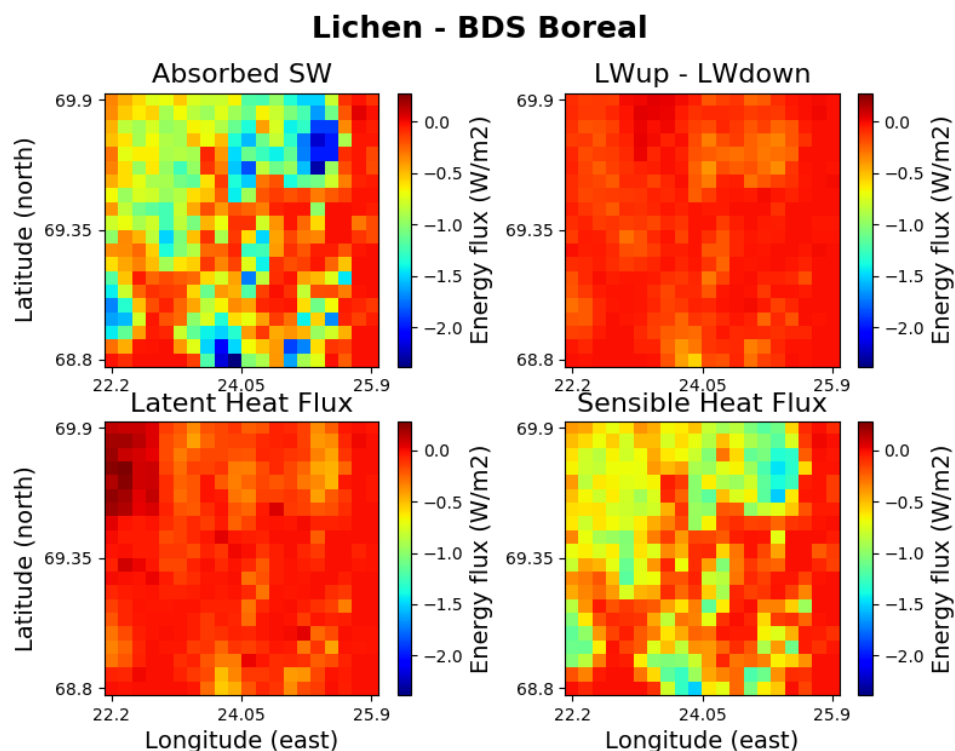


Figure 5.27: Average difference in surface energy fluxes between a run with lichen heath and one where the lichen is replaced by broadleaf deciduous boreal shrub. The average was calculated for 2006-2010.

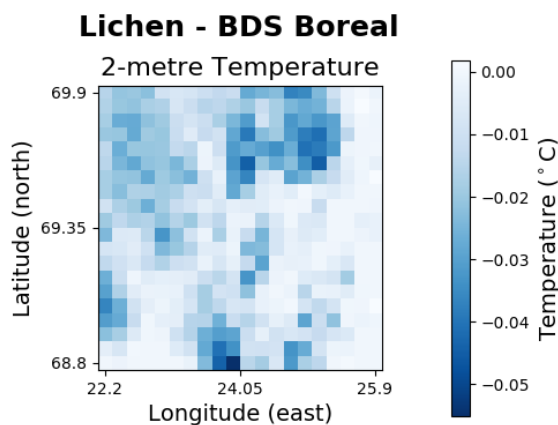


Figure 5.28: Average difference in 2-metre temperature between a run with lichen heath from the distribution model and one where the lichen is replaced by broadleaf deciduous boreal shrub. The average was calculated for 2006-2010.

Discussion for Yearly Average

The average differences in surface energy fluxes have the same signs as the yearly averages calculated for the idealised cases in section 5.3. The higher temperature when lichen has been replaced by shrubs, and lower when replaced by bare ground are also the same trends as we saw for the yearly average 2-metre temperatures in the previous section. The changes in fluxes and temperature when lichen is replaced by shrubs or bare ground can therefore be explained by the same effects that explains the differences in fluxes and temperature between PFTs in the previous sections.

The differences in the idealised cases were larger than the differences here, as would be expected when only parts of the area were covered by lichen. However, the changes when replaced by shrubs are a smaller fraction of the averages found in the idealised case than when lichen is replaced by bare ground. This could be because the model calculates surface energy fluxes and temperature separately for vegetated and non-vegetated surfaces, and the calculations for bare ground differ in many cases from the equivalent calculations for vegetation.

5.5 Results of Canopy Water Experiment

Two experiments with lichen were performed as described in section 3.3 to find a value for maximum canopy water and to look at the timescale of drying.

Maximum canopy water

Figure 5.29 shows the lichen sample as dry on the left hand side and as wet on the right hand side. While the sample was dry it was light, stiff and fragile, and could easily crumble from being touched. After having been filled with water the lichen became soft and sponge-like, and filled more of the box. Still, there was very little change in colour, supporting the assumption that whether the lichen is wet or not does not have a much effect on the albedo (section 4.3).

Table 5.2 shows the wet and dry weights of the two lichen samples. There are two different dry weights: The *initial dry weight* is the weight at the start of the experiment (after having been inside for months), and I call the weight after drying outside for the *final dry weight*. Sample 2 gave some problems due to its small size: at the beginning of the experiment without plastic, the wet weight was too low because the lichen was already dry on top after dripping of



(a) Dry lichen.



(b) Wet lichen.

Figure 5.29: The lichen sample before and after being filled with water.

overnight. For the experiment with plastic, sample 2 was therefore not let to drip of overnight. Since the results for sample 2 are less reliable I have mostly focused on the results for sample 1 but the results for both samples can be found in appendix C. For sample 1, the larger wet weight with plastic than without is likely because the sample was able to take up more water when it did not start out as completely dry. The results for the experiment with plastic may therefore be more realistic, as we do not expect lichen to become as dry in nature as the initial dry weight.

Table 5.2: Measured weight of the two lichen samples in dry and wet conditions for the two experiments. Initial dry weight is the weight after the samples have been inside, wet weight is the weight after having been filled with water and dripped of over night and final dry weight is the minimum weight during the drying period.

Sample 1		Sample 2	
Condition	Weight	Condition	Weight
initial dry weight	289 g	initial dry weight	22 g
wet weight without plastic	852 g	wet weight without plastic	51 g
wet weight with plastic	944 g	wet weight with plastic	70 g
final dry weight		final dry weight	
without plastic	528 g	without plastic	21 g
final dry weight		final dry weight	
with plastic	590 g	with plastic	21 g

From the weights in table 5.2 I can calculate the maximum canopy water. When the lichen got wet its surface area and height increased somewhat (see table C.1 in appendix C). I use the surface area for wet lichen since the lichen cover the

same ground even if it is dry. For the experiment without plastic this gives

$$W_{can,max} = (0.852 \text{ kg} - 0.288 \text{ kg}) / 0.0816 \text{ m}^2 = 6.91 \text{ kg/m}^2 = 6.91 \text{ mm} \quad (5.2)$$

6.91 mm is more water than the 4.21 mm taken from Bello and Arama (1989), but still the same order of magnitude. However, the lichen probably never dries up as completely as it has for the initial dry weight and it could therefore be more realistic to use the final dry weight as the zero canopy water, which gives a maximum canopy water of 3.97 mm. The corresponding values for the experiment with plastic are 8.03 mm and 4.34 mm. The two values calculated with the final dry weight are even closer to the model value than I would expect from a more or less random sample of lichen. The lichen sample would have dried some more in the absence of precipitation, but it was slowing down at this point. Nonetheless, it seems reasonable to assume that the maximum canopy water lies between 3.97 and 8.03 mm for this sample. Considering that this sample is unusually thick, and thicker than what I set as the canopy top height in the model, a general value for the maximum canopy water is probably less than 8 mm. For sample 2 the maximum canopy water was 1.91 mm. This is less than half of what was set in the model, but *C. stellaris* (sample 1) is the most widespread lichen species in Finnmark (Tømmervik et al., 2014) and the results for sample 1 are therefore probably closer to what we would find in Finnmark. This indicates that the model value, taken from Bello and Arama (1989), is a good choice that gives a realistic maximum canopy water.

Timescale of Drying

Canopy water for vascular plants is water that lies on top of leaves and stems and is evaporated from there. For lichen the water is instead taken up by the fungi part of the lichen, and as such it is not as available for evaporation as it is for plants. My implementation of lichen in CLM4.5 does not include this effect, and it is therefore of interest to compare the rate of evaporation in the model with measurements.

Figure 5.30 shows how sample 1 dried with time for the two experiments and the model. The canopy water is shown as fractions of maximum canopy water, and the final dry weight for each of the experiments were used as zero canopy water.

We see from the figure that, while the two experiments had different wet and final dry weights, their rates of drying are quite similar. The experiment with plastic dries somewhat slower, as expected when we no longer have the unwanted

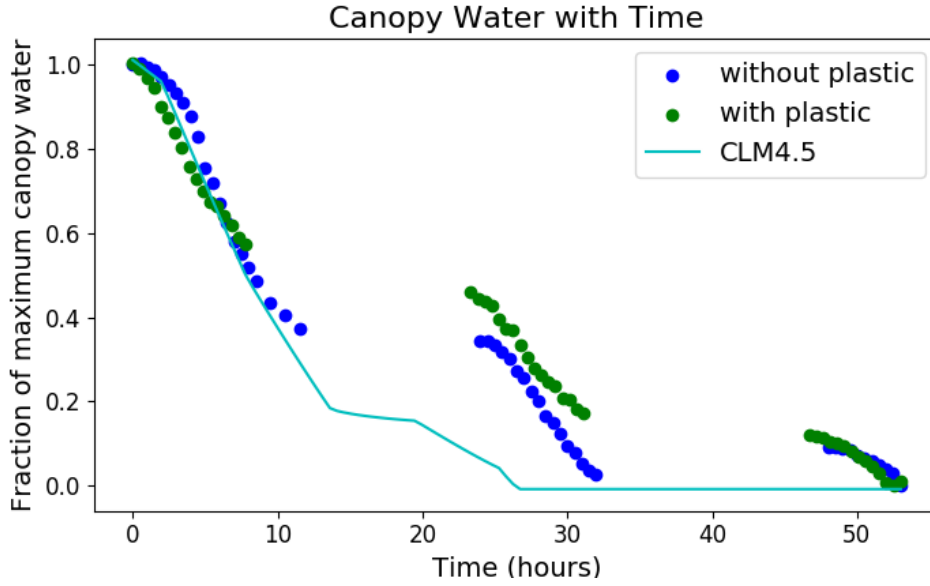


Figure 5.30: Fraction of maximum canopy water in lichen for the two experiments and from CLM4.5. The minimum weight measured in each experiment was used as the limit for no canopy water. Measurements were taken every 30 minutes during the day but not during the night. For CLM4.5 the canopy water is given every 30 minutes.

drying at the sides. The weather conditions were not exactly the same either, so differences can also be due to this. Comparing the model with these rates, we see that it had a very similar rate of evaporation for the first 12 hours. After this, the model had a larger rate of evaporation than what was found in the experiments.

Part of the reason for this could be the fact that the experiments were performed a different place and at a different time than the model run. However, the maximum solar altitude was almost the same, reaching just above 40° altitude both for Finnmark in July and for Oslo in the end on April. Of course the model run receives solar radiation at night as well, while the sun is below the horizon for approximately 10 hours in the experiments, but this is small amounts. From looking at the downward LW from the atmosphere and the absorbed SW in the model, it seems like the days when lichen dries do not have much clouds. During the experiment the cloud fraction varied but the samples were rarely shaded by clouds. In regards to wind, the model varies between 0 and 6 m/s while the experiments were performed for wind between 0 and 5 m/s. For temperature the model range was 6 to 11°C , while the experiments had temperatures between 2

and 17°C. So while the experiment and model run are performed different places at different times, the meteorological conditions were not very different. Still, the model results might be a consequence of other parameters for lichen being wrong, e.g. the albedo or the emissivity.

The other reason for the differences, especially after the first day, is the way the model simulates evaporation of canopy water, with all the water available for evaporation. A better representation for lichen could be to include a resistance for evaporation. One simple and numeriacally cheap way of doing this could be to use an empirical equation that only lets part of the canopy water be available for evaporation, e.g. $W_{avail} = W_{can}e^{-t/\tau}$ where τ is decided from measurements. Another way to do it is to divide lichen into layers. As mentioned in the discussion of section 5.2, the top of the lichen dries much faster than the bottom. A larger resistance to evaporation in the bottom layer than the top layer might make the evaporation more realistic. However, the fact that the lichen from my experiment was still wet at the bottom after three days of drying suggests that the evaporation from the bottom part might not be important and can simply be ignored.

It should be noted that the frequency of precipitation is important. Assuming that the lichen manages to dry between the rainfalls, the same amount of water must evaporate, independent on the rate of evaporation. However, if this is not the case, less of the water will be taken up by the lichen if the rate of evaporation is slow, resulting in a smaller average latent heat flux.

5.6 Further Work

Validate Results with Measurements

The lack of observations is the most problematic aspect of this thesis. It is difficult to defend my implementation of lichen without measurements to substantiate my results. From the canopy water experiment I have some validation that the maximum canopy water is reasonable, and the experiment is also a start in regards to validating the latent heat flux and the timescale of drying. However, measurements to justify the rest of my parameter choices are a very important next step if the lichen PFT is to be used further.

SW and LW radiation sensors to measure the incoming and reflected SW, and the incoming and outgoing LW should be used to validate if the lichen parameterisation gives realistic radiation fluxes. Also, we could use the eddy covariance

method to measure latent and sensible heat fluxes over different vegetation. This would make it possible to verify if the lichen parametrisation does indeed give realistic turbulent fluxes for lichen, and would be better than my experiment for validating the latent heat flux. A challenge with this method is that it requires a relatively large area with lichen cover. Another useful variable to measure is the moisture in lichen. Soil moisture can be determined by satellites that measure temperature and emissivity, and make use of the emissivity's dependence on soil moisture (Kerr et al., 2010). Satellite measurements like this might be used to measure lichen moisture, although the resolution would be a problem since lichen rarely cover areas of the needed resolution (tens of kilometres) alone.

Active Atmosphere

As mentioned, CLM4.5 has been run offline, that is without an active atmosphere, throughout this thesis. This excludes important feedback mechanisms, and an active atmosphere is therefore a natural next step. Especially the temperature is affected by this, as both the surface temperature and the 2-metre temperature are dependent on the air temperature from the atmospheric forcing. The net LW and the sensible and latent heat fluxes are also affected by this through their dependence on the temperatures. Additionally, changes in evapotranspiration could potentially give changes in humidity, precipitation and cloud cover. An active atmosphere would make it possible to quantify such changes and potential feedback mechanisms.

CLM5.0

Since starting this thesis a new version of CLM have been released, CLM5.0. The model builds on CLM4.5 with the most important changes made to soil and plant hydrology, snow density, river modelling, carbon and nitrogen cycling and coupling, and crop modelling (Lawrence et al., 2018). For this study, the changes of most interest is those done to soil and plant hydrology. There is a new parameterisation for soil water evaporation resistance. Canopy interception is now divided into liquid and solid phases, with unloading-events for snow, and the snow covered fraction of canopy is used in the calculations of canopy radiation and surface albedo. The rooting profiles for water and carbon are now consistent, some changes are done to the roots of a few PFTs, and the soil water calculations are improved. Finally, the model introduces variable soil depth which is very important for the amounts of available water in the soil, and in extension, the latent heat flux. However, the shallowest soil depth possible in

the new version is 0.4 m (Lawrence et al., 2018) which still might be too thick for the areas where lichens grow (Smith et al., 2015), but using CLM5.0 would likely make the soil evaporation more realistic. For a more detailed description of the new model version see Lawrence et al. (2018).

Dynamic Vegetation

In a changing climate it is natural to want to simulate how lichen cover might change in the future. To do this the dynamic vegetation mode must be used, which means that all parameters needed for this mode must be set for lichen. This also means that lichen must have photosynthesis because the carbon balance in CLM4.5 decides how much the PFT grows: the amount of carbon in the different parts of the PFT (e.g. leaf, stem, root) determines the leaf and stem area indices, the vegetation height and the fractional cover (Levis et al., 2004). This means that parameters for carbon and nitrogen must be specified. Additionally, the PFTs compete for water to determine productivity (Levis et al., 2004), which might impose a problem for lichens as they do not have roots. Productivity limitations for lichen would therefore need to be dependent on the canopy water rather than soil water and root fractions.

One of the main challenges of making lichen dynamic is to make sure that the model produces realistic occurrences of lichen. One possibility to achieve this could be to separate grid cells depending on topography, assuming that soil depth is typically shallower at larger heights. This would make it possible to make lichen occurrence dependent on soil depth, as lichen typically grows where the soil is shallow. Another, perhaps better, solution is to let lichen have a better chance at growing where other PFTs do not grow, since lichens typically dominate areas that are not favourable for other types of vegetation (Asplund and Wardle, 2017). The more challenging part is then the cases where lichen grows together with other vegetation, although lichen's properties might not be very important together with other PFTs.

Grazing

Part of the motivation behind this thesis was the fact that grazing reduces the lichen cover, and the question of how this might impact the surface energy balance and the local climate. This thesis has quantified the changes for the surface energy fluxes that occurred when lichen in lichen heath was replaced by bare ground or shrubs. I have not taken into consideration how much of the lichen would disappear as a consequence of grazing, but rather removed all lichen as

an extreme case. Also, lichen contributions from other vegetation types are not included (see subsection 3.2.1). A better understanding of the consequences of grazing could therefore be achieved by including these factors. Additionally, the vegetation that replaces lichen is very important, and the excising PFTs are not necessarily a good representation of this type of vegetation. This is typically low shrubs like crowberry (Anders Bryn, personal communication), which could be represented in a separate PFT.

What is clear from previous studies (see subsection 2.2.2) is that reindeer grazing does reduce the amount of lichen. And, due to the lichen's light colour, this will reduce the surface albedo. However, reindeer grazing likewise reduces the shrub cover, which also effects the surface energy balance. The reduction can give an increase in the summer albedo (te Beest et al., 2016), having the opposite effect of reduced lichen. Reduced shrubs additionally delay the snow melt, which also increases the albedo (Cohen et al., 2013). Whether lichen is removed by grazing or due to shrub expansion (as a consequence of climate change) will therefore have different effects on the surface energy balance. Consequently, the effects of reindeer grazing cannot be quantified by looking at changes in lichen cover alone.

Improvements of the Lichen Implementation

The best way to implement lichen is a matter of discussion. I chose to represent lichen as a plant functional type, but since lichen is not in fact a plant this might not be the best representation. One possibility to improve the representation of lichen could be to make some adjustments to the existing PFT-construct. Another possibility is to do something similar to what Porada et al. (2016) did and represent lichen as a possible top layer of the soil. What representation is best will also depend on what the goal is: whether it is to look at effects of grazing, climate change, permafrost or something else. For example, while grazing is an external forcing and do not need dynamic vegetation, this is needed if we want to look at climate change. Or if we want to look at permafrost, it is important that lichen's insulating properties are well represented.

If we are to base our implementation on the existing PFT, one possibility that could improve the implementation is to divide the PFT into layers as describe in section 5.5. However, the lack of cooling effect of lichens on the soil described in subsection 5.3.1 suggests that including lichens as a soil layer, with associated thermal conductivity, might be a better approach if the focus is e.g. permafrost. Having lichen as a soil layer would also make it possible to have lichen growth independent from other vegetation. This would remove the problem of

competition between vegetation and would allow lichen to grow together with other vegetation.

Chapter 6

Summary and Concluding Remarks

The importance of lichens on the surface energy balance and temperature was investigated by using CLM4.5, with a focus on Finnmark. Lichen was implemented as a new PFT, with parameters choices based on previous studies of lichens. Idealised model runs for a single column with only one PFT was performed to look at differences between lichen and other vegetation, both hourly and for monthly averages. It was found that the vegetation cover was most important in May, June and July, and the hourly differences therefore focused on July as this month additionally had no snow cover.

Sensitivity tests were carried out to find which parameters were most important for the surface energy fluxes. It was found that the optical parameters were most important of the tested parameters. However, the removal of transpiration from lichen is the parameter choice that separates lichen the most from the other PFTs.

The albedo of lichen was lower than for shrubs and grass, but the differences were smaller than what was expected from lichen's light colour. This was due to the lower reflectance for lichen than vascular plants in the near infrared part of the spectrum. For bare ground the albedo depended on the soil colour, and since this was relatively light in the areas where I had lichen, the albedo of bare ground was higher than for lichen.

The net LW was mostly dependent on the temperature, being larger for higher temperatures. The sensible heat flux was also dependent on temperature, and connected to the latent heat flux, being smaller when the latent heat flux was large, and larger when the latent heat flux was small.

On average, the latent heat flux was smaller for lichen than for shrubs and grass. This was because lichen had no transpiration. However, lichen can have a large latent heat flux for a longer time after precipitation than other PFTs, due to the large maximum canopy water for lichen compared to other vegetation. Compared to bare ground, lichen had lower latent heat flux, but this was probably unrealistically high for bare ground because the soil was too deep.

The temperature depended on all the surface energy fluxes, the absorbed SW and the latent heat flux being most important, and also on the atmospheric forcing data. On average for the idealised cases the 2-metre temperature did not differ much between lichen and other PFTs, except for shrubs which were 0.2 K warmer, mainly due to its low albedo. During summer the differences were more pronounced, with higher temperature for lichen than for grass and bare ground due to the smaller latent heat flux for lichen as well as due to the lower albedo for lichen than bare ground. However, the temperature lacks important feedback mechanisms because the model was run offline. The difference between PFTs is therefore probably larger than what was found here.

In addition to the idealised cases, a model run with estimated lichen heath amounts for Finnmark was used to find how realistic amounts of lichens impact the surface energy balance. When comparing this with runs where lichen had been replaced by other PFTs we could recognise the same features as found in the idealised cases. The changes were naturally smaller, indicating that the changes in lichen cover potentially must be quite significant to get a signal. It is also clear that what type of vegetation lichen is replaced with is important. If lichen is replaced by shrubs, e.g. as a consequence of a warmer climate, these results indicate that the temperature will increase. But if lichen is instead replaced by bare ground, the results indicate that the temperature will decrease. However, since the latent heat flux is too large for bare ground, the ground is cooled too much. The soil colour is also important, and a darker soil colour may give an increase in temperature instead, especially if the latent heat flux is smaller.

The soil thickness is most likely a significant source of error when comparing lichen with bare ground because lichen typically grows on shallow soil. Additionally, the lack of validations of the parameter choices is an important limitation of the study. Measurements of maximum amount of water and rate of drying for lichen was performed as a start to validate the parameter choices, but more validation is needed. Doing something about these two points are important next steps too get a more reliable answer to the question of lichen's importance to the surface energy balance. Additionally, the average difference in 2-metre temperature found in this thesis may not be pronounced, but we would get a better

indication of temperature differences if we had included an active atmosphere, which is a natural next step.

My results indicate that lichen has surface energy fluxes that differ considerably from other vegetation. It is therefore worthwhile to include lichen in LSMs when investigating the surface energy balance in polar and high altitude regions. Since lichen is also a type of vegetation that is likely to change due to anthropogenic influences like reindeer husbandry or climate change, it is important when looking at impacts of vegetation changes in these regions.

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Appendices

Appendix A

Lichen Parameterisation

Table A.1 lists all the parameters chosen for lichen, including value set, where it is set and what it is called where it is set. Most of the parameters are set in *pftdata*. This is an input file to CLM that contain most of the PFT parameters. The parameters that can potentially change from month to month are set in *surfdata*. This is also an input file used in CLM that contains surface data, e.g. soil colour, soil composition, lake depth etc. Additionally a few of the variables are set directly in the code.

Table A.1: Overview over the parameters choices for lichen, where they are set and the name where they are set. VIS = visible, NIR = near infrared.

Parameter	Value	Place	Name
Top height	0.1	surfdata	MONTHLY_HEIGHT_TOP
Bottom height	0.01	surfdata	MONTHLY_HEIGHT_BOT
Leaf area index	0	surfdata	MONTHLY_LAI
Stem area index	2.5	surfdata	MONTHLY_SAI
Root distribution parameter a	0	pftdata	roota_par
Root distribution parameter b	0	pftdata	rootb_par
Ratio of momentum roughness length to canopy top height	0.120	pftdata	z0mr
Ratio of displacement height to canopy top height	0.68	pftdata	displar
Characteristic dimension of the leaves in the direction of wind flow	0.04	pftdata	dleaf
Reflectance for leaf, VIS	n/a^a	pftdata	rholveis
Reflectance for leaf, NIR	n/a^a	pftdata	rholveis
Reflectance for stem, VIS	0.34	pftdata	rhosvis
Reflectance for stem, NIR	0.37	pftdata	rhosnir
Transmittance for leaf, VIS	n/a^a	pftdata	rholveis
Transmittance for leaf, NIR	n/a^a	pftdata	rholveis
Transmittance for stem, VIS	0.120	pftdata	rhosvis
Transmittance for stem, NIR	0.250	pftdata	rhosnir
Deviation of leaf angles from a random distribution	0.01	pftdata	xl
Maximum canopy water per leaf and stem area	1.68	in code	dewmx
Alpha parameter	1	in code	n/a^b

^aThis parameter is not needed because the leaf area index is set to zero.

^bThis parameter is set directly in the equation for interception without being defined.

Appendix B

Leaf and Stem Area Indices

Table B.1: LAI and SAI for BDS Boreal and arctic grass.

	BDS Boreal		Arctic Grass	
Month	LAI	SAI	LAI	SAI
Jan	0	0.5	0	0.5
Feb	0	0.5	0	0.5
Mar	0	0.5	0	0.5
Apr	0.29995855	0.5	0.27493782	0.5
May	0.60000002	0.5	0.60000002	0.5
Jun	1.22502075	0.5	1.22502075	0.5
Jul	2.02506214	0.5	2.02502071	0.5
Aug	1.92497925	0.55004147	1.92497925	0.52502074
Sep	1.47502072	0.69999999	1.5	0.69999999
Oct	0	1.8750207	0	1.82497923
Nov	0	0.89999998	0	0.92497925
Des	0	0.5	0	0.5

Appendix C

Data from Canopy Water Experiment

Table C.1 shows the size of the lichen samples while dry and wet for the two experiments.

Table C.1: Measured height, length and width of the two lichen samples in dry and wet conditions.

	Height	Length	Width	Surface Area
Lichen 1, dry	12 cm	30 cm	20 cm	600 cm ²
Lichen 1, wet	13 cm	34 cm	24 cm	816 cm ²
Lichen 2, dry	6 cm	15 cm	15 cm	225 cm ²
Lichen 2, wet	8 cm	16 cm	16 cm	256 cm ²

Table C.2 shows the measurements taken of the two lichen samples from 18.04.18 to 20.04.18. Weight 1 and weight 2 are the weights of sample 1 and 2, respectively (as described in section 3.3).

Table C.2: Experiment log from 18.04.18 - 20.04.18. Showing when the measurements are taken, weights of the samples, cloud cover and other notes. Horizontal lines signifies a new day. Sample 2 is not weighted as long as sample 1 since it dried much faster.

Time	Weight 1	Weight 2	Clouds	Other
08:20	852 g	51 g	8/8	Humid
08:50	853 g	50 g	8/8	
09:20	850 g	50 g	8/8	

Data from Canopy Water Experiment

09:50	848 g	50 g	8/8	Overcast, but lighter in colour
10:20	843 g	49 g	8/8	
10:50	837 g	48 g	8/8	
11:20	830	47 g	7/8	Cloud cover starting to break up, sun visible through the clouds
11:50	823 g	44 g	4/8	
12:20	812 g	42 g	1/8	
12:50	797 g	37 g	1/8	Lichen 1 starting starting to get dry on the top
13:20	773 g	36 g	1/8	
13:50	761 g	34 g	1/8	
14:20	745 g	33 g	1/8	
14:50	731 g	32 g	4/8	
15:20	716 g	30 g	4/8	
15:50	707 g	28 g	5/8	
16:20	696 g	27 g	6/8	thin cloud cover
16:50	686 g	27 g	6/8	thin cloud cover
17:50	669 g	23 g	6/8	
18:50	659 g	27 g	6/8	
20:00	649 g	25 g	6/8	
08:30	639 g	25 g	6/8	Lichen no longer dry/stiff at the top
09:00	639 g	25 g	6/8	
09:30	636 g	25 g	5/8	
10:00	631 g	24 g	3/8	
10:30	626 g	24 g	4/8	
11:00	616 g	23 g	4/8	
11:30	611 g	24 g	4/8	
12:00	601 g	23 g	3/8	
12:30	593 g	22 g	2/8	
13:00	582 g	23 g	2/8	
13:30	576 g	22 g	2/8	Lichen dry along the sides (despite the box)
14:00	568 g	21 g	5/8	
14:30	558 g	22 g	6/8	
15:00	553 g	23 g	7/8	
15:30	545 g	-	7/8	
16:00	540 g	-	6/8	
16:30	537 g	-	4/8	
08:25	557 g	-	8/8	Fog, humid, small "drizzle".

Data from Canopy Water Experiment

09:00	557 g	-	8/8	Lichen moist and soft.
09:30	556 g	-	8/8	Fog
10:00	555 g	-	8/8	Fog
10:30	551 g	-	8/8	Fog
11:00	549 g	-	8/8	Fog
11:30	547 g	-	8/8	Fog
12:00	544 g	-	8/8	Fog
12:30	541 g	-	8/8	Less fog. Lichen still moist.
13:00	538 g	-	8/8	
14:00	528 g	-	8/8	

The measurements taken for the second experiment are given in table C.3.

Table C.3: Experiment log from 25.04.18 - 27.04.18. Showing when the measurements are taken, weights of the samples, cloud cover and other notes. Horizontal lines signifies a new day. Measurements for sample 2 started the second day.

Time	Weight 1	Weight 2	Clouds	Other
08:40	944 g	-	3/8	Dry weather
09:10	940 g	-	4/8	
09:40	932 g	-	4/8	
10:10	924 g	-	3/8	Lichen starting to dry on top
10:40	908 g	-	4/8	
11:10	899 g	-	3/8	
11:40	886 g	-	3/8	Lichen completely dry on top
12:10	874 g	-	4/8	
12:40	858 g	-	6/8	
13:10	847 g	-	7/8	
13:40	837 g	-	6/8	
14:10	828 g	-	6/8	
14:40	825 g	-	6/8	
15:10	816 g	-	5/8	Some shadow from the fence
15:40	808 g	-	6/8	
16:10	798 g	-	6/8	
16:40	793 g	-	6/8	
08:50	752 g	70 g	1/8	Sample 1 was dry on top (still wet on the sides)
09:20	747 g	66 g	1/8	
09:50	744 g	61 g	1/8	

Data from Canopy Water Experiment

10:20	741 g	55 g	1/8	Sample 2 is dry on top
10:50	729 g	51 g	1/8	
11:20	721 g	46 g	1/8	
11:50	720 g	43 g	1/8	
12:20	708 g	39 g	2/8	
12:50	698 g	36 g	2/8	
13:20	688 g	33 g	2/8	
13:50	683 g	31 g	3/8	
14:20	677 g	29 g	4/8	
14:50	673 g	29 g	4/8	
15:20	663 g	28 g	4/8	
15:50	662 g	28 g	4/8	
16:20	654 g	24 g	2/8	
16:50	651 g	26 g	2/8	
08:40	632 g	25 g	8/8	Sample 1 was half moist on top, sample 2 was dry
09:10	631 g	25 g	8/8	Sample 1 almost dry on top
09:40	630 g	24 g	8/8	Sample 1 dry on top
10:10	627 g	24 g	8/8	
10:40	626 g	24 g	8/8	
11:10	623 g	24 g	8/8	
11:40	619 g	23 g	7/8	
12:10	614 g	23 g	7/8	
12:40	611 g	23 g	5/8	
13:10	606 g	22 g	4/8	
13:40	600 g	25 g	4/8	
14:10	592 g	22 g	6/8	
14:40	590 g	21 g	7/8	
15:10	593 g	23 g	7/8	Light rain have started. Sample 1 is still wet on the sides.