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Sensitivity of the Community Land Model (CLM4.0) to Key Modeling Parameters and Modeling of Key Physical Processes with Focus on the Arctic Environment

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Sensitivity of the Community Land Model (CLM4.0) to Key Modeling Parameters and Modeling of Key Physical Processes with Focus on the Arctic Environment

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ABSTRACT

The purpose of this study was to identify major parameters and physical processes that have greatest impacts on the near surface energy balance in the Arctic environment. The historical data set for the period of 1948 to 2004 from National Center for Atmospheric Research (NCAR) was used to generate atmospheric forcing data for this analysis. The CLM 4.0 (Community Land Model) was used for land simulations of the point grid cell located near Fairbanks, Alaska. A range of hydrogeologic and thermal soil properties and vegetation characteristics were defined for the vegetation and soil data. The current approach used in CLM was modified to simulate soil moisture to allow for more realistic water table representation. Multiple CLM sensitivity runs were analyzed with regard to their effects on the feedbacks to the atmospheric model. This analysis allowed for identifying major parameters and important physical processes with the potential to impact the climate either in the short or long term.

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ACRONYMS

BDS	Broadleaf Deciduous Shrub
CESM	Community Earth Systems Model
CLM	Community Land Model
FAO	Food and Agriculture Organization
IGBP	International Geosphere-Biosphere Programme
LAI	Leaf Area Index
NCAR	National Center for Atmospheric Research
NET	Needleleaf Evergreen Tree
PFT	Plant Functional Type
SAI	Stem Area Index
SNL	Sandia National Laboratories
SWE	Snow Water Equivalent

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1.0 INTRODUCTION

The Community Land Model (CLM version 4.0) is the land sub-model of the Community Earth Systems Model (CESM version 1). CESM is an open-source, FORTRAN language, global climate model maintained by the National Center for Atmospheric Research (NCAR) in Boulder, Colorado. It is the product of on-going development, which started with the Community Climate System Model (CCSM) in 1983. The other modules within the CESM are for atmosphere (CAM), sea ice (CICE), oceans (POP2), land ice (Glimmer-CISM), and the “coupler” which links the modules together.

CLM approximates the land surface using a grid cell approach. A few different resolutions are available. CLM can be run in a stand-alone mode and in a fully coupled mode. The stand-alone mode can model either single cell or multiple cells (regions).

Each grid cell is defined in terms of its land units. The land units are: glacier, wetland, lake, urban, and vegetated. Each land unit is simulated as a one-dimensional column. The vegetated land unit is defined in terms of plant types (this includes bare soil). The vertical profiles of temperature and soil moisture are calculated for each column.

The physical processes simulated by the CLM include the following:

- Absorption, reflection, and transmittance of solar radiation
- Absorption, reflection, and transmittance of longwave radiation
- Momentum, sensible heat, and latent heat
- Heat transfer in soil and snow
- Canopy hydrology
- Snow hydrology
- Soil hydrology
- Photosynthesis
- Lake temperatures and fluxes
- Dust deposition and fluxes
- Runoff from rivers and oceans
- Volatile organic compounds
- Carbon-nitrogen cycling

The summary technical description of these models is provided in Oleson (2010). Additional details concerning the specific models and modeling parameters are spread over many different supporting publications and studies. Each model represents a different area or even a discipline and this multi-disciplinary aspect is the major reason of the CLM complexity.

The models in CLM have very different levels of representation of the underlying physical processes. Some models significantly simplify the physical processes. An example is the canopy

model in which simple water balance equations are used. The other models use very detail representations of the physical processes. An example is the soil moisture model that implements non-linear modified Richard’s equation (Oleson, 2010). However, all the models are inter-related and they either provide the inputs to a downstream model or use the outputs from an upstream model. Due to this, a few iterations are needed to take into account the feedbacks between the models and to make the necessary adjustments in the calculated state variables during each time step.

The diagram in Figure 1 shows in a simplified form the relationships between the different models. The Sensible Heat, Latent Heat, and Momentum Flux Models are separate and complex models. They are shown in one box because the focus of this analysis was on the hydrogeologic and vegetation models in CLM.

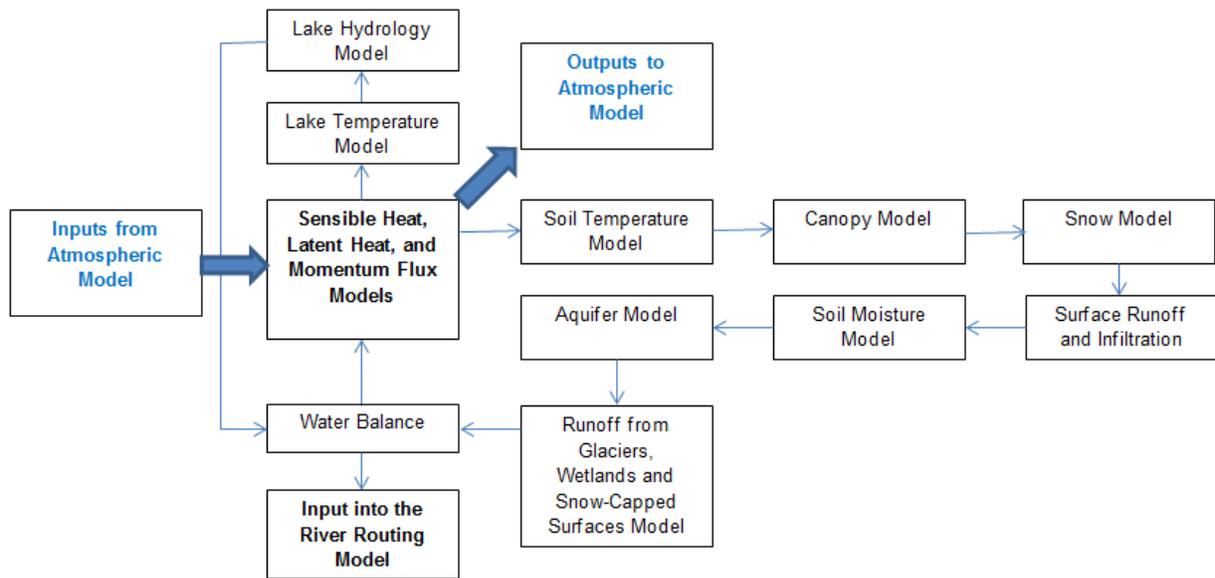


Figure 1. Simplified Diagram of Relationships between the CLM Models.

Note that Sensible Heat, Latent Heat, and Momentum Flux Models represent a direct interface with the atmospheric model. They use the atmospheric model inputs while also contributing to atmospheric model outputs. The vegetation and hydrogeologic models indirectly affect the atmospheric model outputs through their feedbacks to the Sensible Heat, Latent Heat, and Momentum Flux Models. The models with noticeable feedbacks may require detailed physical representation. Our goal was to review the vegetation and hydrogeologic models in CLM with this criterion in mind.

2.0 SENSITIVITY ANALYSIS OBJECTIVES, METHOD, AND PARAMETERS

The hydrogeologic and vegetation models in CLM have a number of simplifying assumptions. The soil column depth is 3.54 m in any grid cell in the world. The hydraulic and thermal properties of soils are defined based on their organic matter, sand and clay content, which is an approximation that may or may not be applicable at a site-specific scale. The temperature boundary condition at the bottom of the bedrock is zero flux. The aquifer, as implemented in CLM, has infinite resources. This limits the simulations of water withdrawal effects. The subsurface drainage parameters are the same in every grid cell and the rooting depth parameters are fixed for each vegetation type.

Our objective was to investigate the potential effects related to some of these assumptions, as well as modeling parameters and physical processes. In order to evaluate the importance of these effects, we considered their impacts on the CLM outputs to the atmospheric model.

The parameters that represent the direct outputs from CLM to the atmospheric model are listed in Table 1. We also considered the state variables and hydraulic parameters listed in Table 1 because they indirectly affect the outputs to the atmospheric model:

Table 1. Parameters Considered in the Sensitivity Analysis.

<u>Direct Outputs into the Atmospheric Model</u>	<u>State Variables and Hydraulic Parameters</u>
Latent heat flux [W m^{-2}]	Ground heat flux [W m^{-2}]
Sensible heat flux [W m^{-2}]	Ground temperature [K]
Water vapor flux [mm s^{-1}]	Soil temperature in top 10 cm [K]
Zonal momentum flux [$\text{kg m}^{-1} \text{s}^{-2}$]	Sub-surface runoff [mm s^{-1}]
Meridional momentum flux [$\text{kg m}^{-1} \text{s}^{-2}$]	Surface runoff [mm s^{-1}]
Emitted longwave radiation [W m^{-2}]	Infiltration [mm s^{-1}]
Direct beam visible albedo	Total runoff [mm s^{-1}]
Direct beam near-infrared albedo	Aquifer recharge [mm s^{-1}]
Diffuse visible albedo	Water table depth [m]
Diffuse near-infrared albedo	Water in unconfined aquifer [mm]
Absorbed solar radiation [W m^{-2}]	Soil ice content
Temperature at 2 meter height [K]	Soil water content
Specific humidity at 2 meter height [kg kg^{-1}]	
Snow water equivalent [m]	

To perform this analysis CESM and the CLM were compiled and run on a supercomputer at SNL High Performance Computing Center. CLM was run in the “stand-alone”, single grid block mode at a resolution of 0.9 x 1.25 degrees. This was the fastest and least data intensive way to perform multiple runs for the sensitivity study. This treatment is possible as CLM assumes each grid block is effectively independent of its neighboring blocks.

Because the arctic environment is especially important in the climate studies, we selected a grid block located in the Fairbanks area in Alaska. The scale of a single grid block at that latitude is 62.1 x 36.25 miles. The coordinates of the grid block corners are provided in Table 2. The map of this area is shown in Figure 2.

Table 2. Study Area Coordinates.

Grid Block Point	Latitude	Longitude
North East	66.316	213.75
North West	66.316	211.25
South East	64.421	213.75
South West	64.421	211.25
Grid Block Center	65.36	212.5

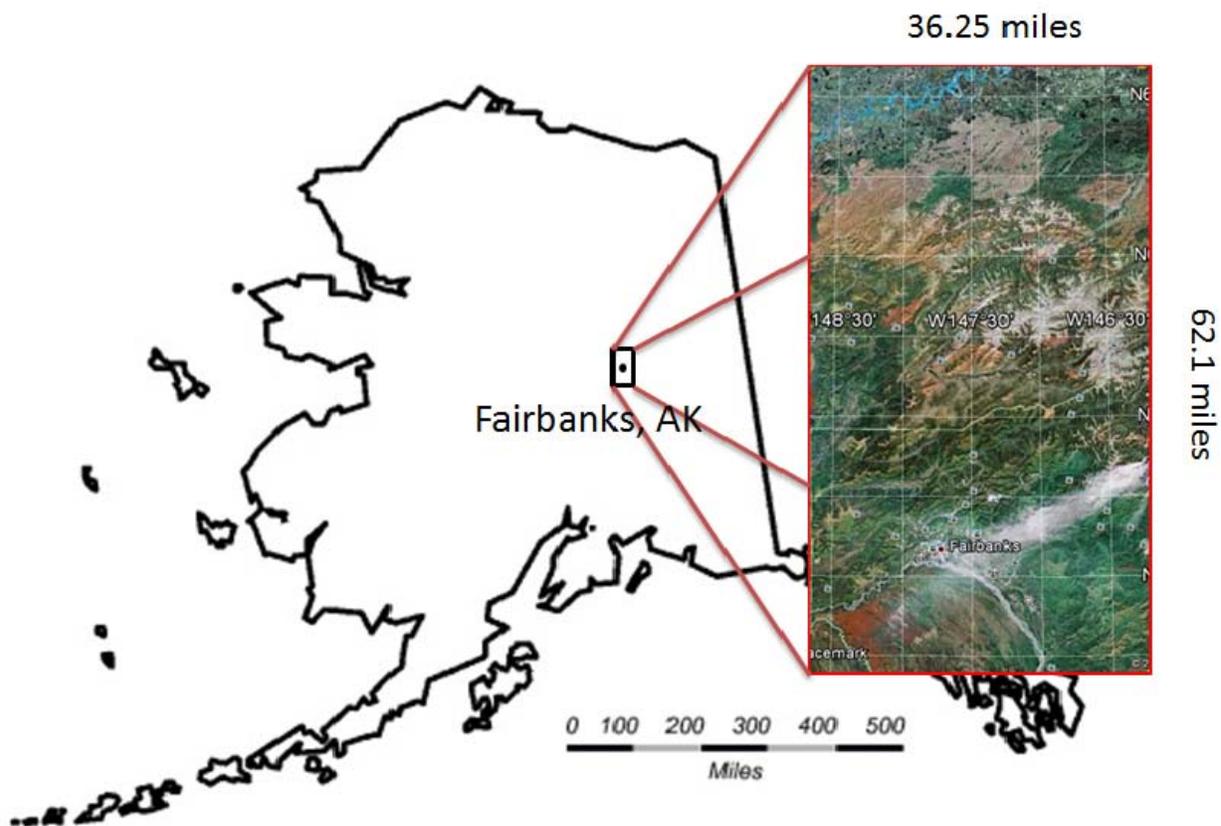


Figure 2. Study Area Map.

A stand-alone CLM run requires an input data set, or forcing data, to take the place of data which would otherwise be provided as output from modules of the CESM. The following parameters are inputs into the CLM:

- Zonal Wind
- Meridional Wind
- Pressure
- Potential Temperature
- Temperature
- Specific Humidity
- Incident Long-Wave Radiation
- Incident Diffuse Visible Radiation
- Incident Diffuse Near-Infrared Radiation
- Incident Direct Beam Visible Radiation
- Liquid precipitation
- Solid precipitation
- Aerosol deposition rate

A historical data set for the CLM, for the period of 1948 to 2004, was compiled by Qian (2006). The atmospheric data are expressed in 3 hour increments, precipitation in 6 hour increments, and solar data in 6 hour increments. These data were obtained from NCAR and looped through 3 times in succession to provide necessary inputs for the model runs. Note that the resulting climate data are the historic data and do not contain any future forecasts.

To bring the model to a common starting point we performed a spin-up run for a period of 60 years starting from 1948. The final state of the model was saved and used as a restart file for all the subsequent runs. After the spin-up run, each of the CLM test runs had a period of 100 to 150 years.

The output from CLM is formatted as a netcdf file. We used Matlab (R2011a) by Mathworks to process and perform initial analysis of the data. Each month of simulation time produces one output file containing land model monthly averages for 189 variables and another coupler file containing monthly averages of 120 variables. The coupler variables are those which would be passed back to the other modules within the CESM. The output variables considered in this analysis (Table 1) are from both, land model and coupler files. Annual averages were generated for soil moisture and soil ice to smooth the data.

The parameters selected for the sensitivity analysis are the surface data and some hard-wired data as described below.

Each grid cell has the following surface data (resolution is shown in parentheses) associated with it:

- Percent glacier (0.5⁰)
- Percent Lake (1.0⁰)
- Percent wetland (0.5⁰)
- Percent urban (1.0⁰)
- Percent sand, percent clay (5-min)
- Soil organic matter density (1.0⁰)
- Soil color (0.5⁰)
- Maximum fractional saturated area (0.5⁰)
- Percent of vegetated land (0.5⁰)
- Canopy height (top and bottom) (0.5⁰)
- Monthly leaf and stem area indices (0.5⁰)

Note that Fairbanks grid cell does not have a glacier, or a lake, or a wetland associated with it.

CLM reads these input data from the surface data file. A number of other data are “hard-wired” in the code and can be changed only via code modification. The examples are: ground emissivity for soil (0.96); momentum roughness length for soil, glaciers, and wetlands (0.01 m); and heat conductivity of bedrock (3.0 W/m-K).

The Fairbanks grid cell has one land unit, which is vegetated land unit as evident from the map in Figure 2. The surface data were extracted from the global dataset using regional extraction routine by specifying the coordinates of the grid cell (Table 2).

Our goal was to consider the following parameters, including applicable surface data and some hard-wired parameters (last two parameters in the list below), in the sensitivity analysis:

- Soil color
- Percent sand
- Percent clay
- Leaf Area Index (LAI)
- Stem Area Index (SAI)
- Canopy bottom and top height
- Rooting depth
- Subsurface drainage

The applicable variability ranges to be used in the sensitivity analysis were defined for each parameter from this list as described below.

2.1 Soil Color

Soil color affects the dry and saturated soil albedos, which, in turn, impact the energy partitioning at the surface. CLM defines 20 different soil colors, each of them has saturated and dry visible soil reflectance and saturated and dry near infrared soil reflectance. The soil colors were defined in CLM for each grid cell using a fitting process to get a best match between the albedos calculated by CLM and MODIS satellite observed surface albedos (Lawrence, 2006). The soil color in Fairbanks grid cell, as defined in the surface data set, is 19. The potential variation in the soil color was obtained from the map in Lawrence (2006) showing the world-wide distribution of the soil color classes. According to this map, the variation of soil color in vicinity of Fairbanks area is from 17 to 20, which corresponds to dark low albedo soils. Two cases with the soil color 17 and 20 were considered.

2.2 Soil Texture (Percent Sand and Percent Clay)

Soil texture (percent sand and percent clay) and organic matter density affects thermal and hydraulic properties of soils. These parameters affects the distribution of moisture and temperatures in soil column, ground temperature and surface moisture, which in turns impact the sensible heat, latent heat, and ground heat fluxes.

The soil properties in the Fairbank grid cell are listed in Table 3. Note that only percent clay and percent sand are specified. It is assumed that the remainder percentage is silt.

Table 3. The Fairbanks Grid Cell Soil Textural Properties.

Layer NN	1	2	3	4	5	6	7	8	9	10	Mean
% sand	40	39	39	44	44	48	47	47	49	49	45
% clay	31	32	32	26	26	25	25	25	27	27	28
ρ_{om} (kg/m ³)	130	130	130	130	95	61	38	14	0	0	

NOTE: ρ_{om} is the soil organic matter density.

As was discussed earlier, the soil column depth is fixed and is 3.54 m. The soil column is represented with 10 layers with the layer 1 being at the column top. The layer thickness increases exponentially with depth.

There are a number of assumptions associated with the soil models in CLM. The previous CLM versions implemented one set of grid cell specific textural properties for the first 5 top soil layers (depth from 0 to 0.29 m) and second set for the bottom 5 soil layers (depth 0.29 m to 3.63 m). These data were directly prescribed from the global soil profile texture data sets of Reynolds (1999). Originally, these data sets were derived from the FAO/UNESCO Digital Soil Map of the World (Food and Agriculture Organization, 1995) using the depth and profile methods used by Batjes (1997). Note that FAO/UNESCO data provides information for two soil layers: top soil (depth 0 to 0.30 m) and bottom soil or subsoil (depth 0.30 m to 1.00 m). The bottom soil data were assigned to the CLM soil layer depth 0.29 m to 3.43 m (the lower limit was arbitrarily extended).

In the latest version (CLM4.0) the textural properties (including organic matter density) are prescribed to each of 10 soil layers for each grid point. These more detailed data were derived from the International Geosphere-Biosphere Programme (IGBP) soil data set (Global Soil Data Task, 2000). Note that IGBP data set used the same base data and methods as FAO/UNESCO, Reynolds et al. (1999), and Batjes (1997), but with the finer resolution.

Five hydrologically inactive ground layers are added to the soil column in order to extend the overall depth to approximately 50 m. These additional layers represent bedrock and are used in the temperature model. Because these layers are hydrologically inactive, the moisture calculations are restricted to the upper 10 layers.

To derive the upper and lower limits for the sand and clay content in the Fairbanks grid cell, the following information was taken into account.

- (1) The coefficients of variation of individual soil properties within soils mapped as single series commonly range from 20% to 70%. These coefficients can even be larger when soils are mapped at a higher hierarchical level, such as the FAO soil unit (Batjes, 2002).
- (2) According to the distribution of the textural properties of the top soil in the world-wide soil property map in Lawrence (2008), the clay content in the vicinity of the Fairbanks area is from 10% to 30% and the sand content is from 30% to 60%. Consequently, the clay content in Table 3 is close to its upper limit and the sand content is close to its average value.

Four cases were considered to represent the variability in soil properties: sand content-10%; sand content+10%; clay content-10%, and clay content-20%.

2.3 Vegetation Parameters LAI and SAI

Vegetation parameters affect interception of precipitation and evapotranspiration and thus the distribution of moisture in the soil column and heat and moisture exchange at the ground surface.

Vegetation structure is defined by the leaf area index (LAI), stem area index (SAI) and the canopy bottom and top height. Monthly values of LAI and SAI are defined in CLM for each plant functional type (PFT). LAI is a dimensionless variable defined as one half of the total leaf area per unit ground surface area. SAI is defined as the total area of all the plant stems per unit ground surface area. Monthly LAI values in CLM were developed from the 1-km MODIS-derived monthly grid cell average LAI of Myneni (2002). SAI is calculated from the monthly PFT LAI values using methods of Zeng (2002).

There are 3 major vegetation types in the Fairbanks grid cell. These types are: Needleleaf Evergreen Tree (NET) Boreal; Broadleaf Deciduous Shrub (BDS) Boreal; and Arctic Grass. A typical landscape for the Fairbanks area is shown in Figure 3.



NOTE: This photo is from the Google Earth photographs

Figure 3. Typical Landscape in Fairbanks Grid Cell.

The area occupied by each plant functional type (PFT) expressed as a percent of total vegetated area and the plant specific parameters are presented in Table 4.

Table 4. Plant Functional Type (PFT) Characteristics for Fairbanks Grid Cell.

PFT	% Area	Mean LAI	Mean SAI	Canopy Bottom, m	Canopy Top, m
NET Boreal	60.45	2.426	0.683	8.5	17.0
BDS Boreal	13.5	0.830	0.917	0.1	0.5
Arctic Grass	17	0.838	0.939	0.01	0.5
Total	90.95				

The monthly LAI and SAI values for the three PFTs are shown in Figure 4. These data are based on the satellite phenology data for year 2000. The needleleaf forest (NET Boreal) occupies the largest area, has the greatest LAI values and is significantly higher than the other PFTs. Because of this, this PFT was considered in the sensitivity analysis.

The published LAI values for a forest range from 0.4 to 14. The common range for the maximum values is from 6 to 8. To acknowledge this potential variability, 2 cases shown in Figure 4 were considered. In the first case, the LAI values are greater by factor of 2 (LAIx2 case). In the second

case, the LAI values are smaller by factor of 2 (LAIx0.5 case). Same principle (factor of 2) was applied to the SAI values (SAIx2 and SAIx0.5 cases). LAIx2 and SAIx2 cases correspond to the dense vegetation and LAIx0.5 and SAIx0.5 correspond to scarce vegetation.

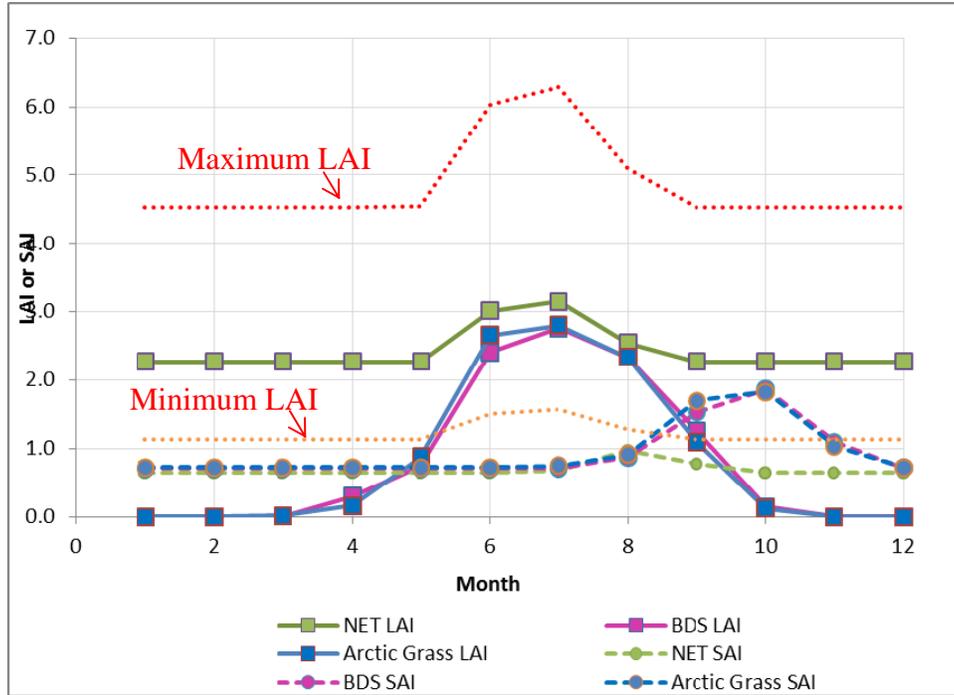


Figure 4. Monthly LAI and SAI of the Dominant PFTs in Fairbanks Grid Cell.

2.4 Canopy Top and Bottom Height

The canopy top and bottom height affects the plant aerodynamic parameters, which in turn affect the surface fluxes. These parameters are specified for each PFT. The monthly values of all three PFT types present in the Fairbank area are constant. These values are listed in Table 4.

In most of the boreal forests, the dominant trees are needleleaf evergreens-either spruce and fir or spruce and pine. Boreal forests have the simplest structure of all forest formations. They have only one uneven layer of trees. The majority of these tree species are 15 to 45 m tall. The canopy top height in Table 4 is closer to the lower limit of this range. To take in account this variability, two additional values for the canopy top height were considered – 23 m and 30 m. The canopy bottom is defined as one half of the canopy top. This ratio was preserved in the above cases.

2.5 Root Distribution Parameters

The root distribution parameters affect the evapotranspiration and thus the distribution of moisture in the soil column and the heat and moisture exchange at the surface.

The cumulative root distribution function (Y) is defined in CLM with two parameters - r_a and r_b . This function is represented after Zeng (2001) as:

$$Y = 1 - 0.5[e^{-r_a d} + e^{-r_b d}] \quad (1)$$

where d is depth. The effective rooting depth is defined as the depth interval that contains 99% of roots. The parameters r_a and r_b are PFT specific. The values of r_a and r_b for NET Boreal are 7 and 2 respectively. The resulting effective rooting depth is 1.8 m (Figure 5).

As discussed in Day (2010), the shallowest maximum rooting depth of trees is 1 m. The soil depth in CLM is fixed at 3.54 m. Consequently, it is reasonable to assume that the effective rooting depth range from 1 m (shallow roots) to 3.54 m (deep roots). These two cases were considered in the sensitivity analysis.

The values of the parameters r_a and r_b that result in the shallow and deep roots were estimated from Equation (1). The goal was to find the combination of these parameters that would result in the desirable effective rooting depth while maintaining the same functional shape within the 0 to 50% interval. The major differences would then be for the root distribution within the 51% to 99% interval. The resulting parameters are summarized in Table 5. The resulting root distribution functions are shown in Figure 5.

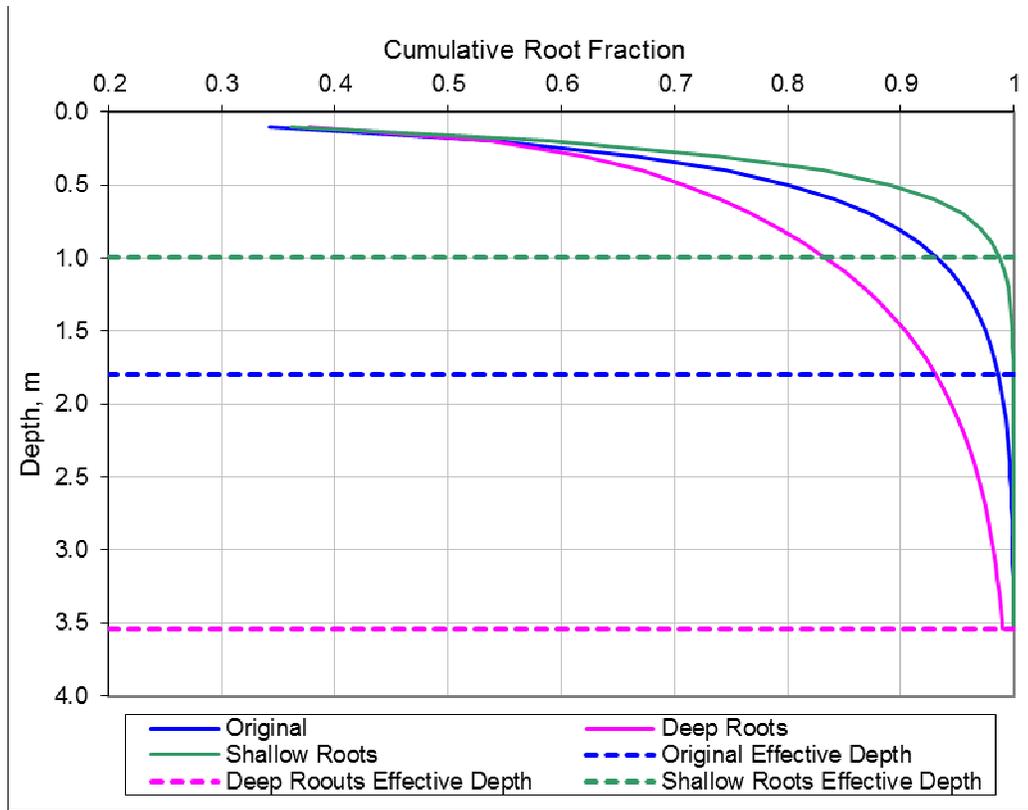


Figure 5. Original and Modified Cumulative Root Distribution Functions.

Table 5. Original and Modified Cumulative Root Distribution Parameters.

Parameter	Original Values	Modified Parameter Values	
		Deep Roots	Shallow Roots
Effective Rooting Depth (m)	1.8	3.54	1
r_a (1/m)	7	10.5	5
r_b (1/m)	2	1.1	4

2.6 Subsurface Drainage Parameters

The subsurface drainage controls the moisture conditions in the soil column and the depth to the water table.

The subsurface drainage q_{drai} is calculated in CLM during each time step as:

$$q_{drai} = (1 - f_{imp})q_{drai,max} \exp(-f_{drai}z_{\nabla}) \quad (2)$$

where f_{imp} is the impermeable land fraction, f_{drai} is the decay factor, $q_{draimax}$ is the maximum drainage when the water table depth is at the land surface, and z_{∇} is the time-dependent depth to water table. The parameters $q_{draimax}$ and f_{drai} are hard-wired in CLM. The respective values are $0.005 \text{ kg/m}^2\text{-s}$ and 2.5 m^{-1} . These two parameters were determined through sensitivity analysis and comparison with the observed runoff (Olsen 2010). They are the same at any location (grid cell) in the world. The subsurface drainage as a function of the water table depth is shown in Figure 6.

The drainage parameters, as defined in CLM, result in very small fluctuations of the water table and keep the water table depth around 3 m below the surface, which is at the bottom part of the soil column (Figure 7). This is because every time when the water table rises, the subsurface drainage increases exponentially, the excess water is quickly removed, and the water table drops. Every time when the water table drops, the drainage stops, and the water table rises. As a result, the shallow water table conditions (saturated soil column) and deep water table conditions (dry soil column) are not effectively represented.

The subsurface drainage parameters were modified as summarized in Table 6. The modified subsurface drainage functions are shown in Figure 6. The modified parameters allowed for simulating the shallow water table conditions as shown in Figure 7. Note that the shallow water table conditions are of a special importance because these conditions are common for the arctic environment, including the Fairbanks grid cell. These conditions results in multiple zones of discharge, such as a small lake shown in Figure 3.

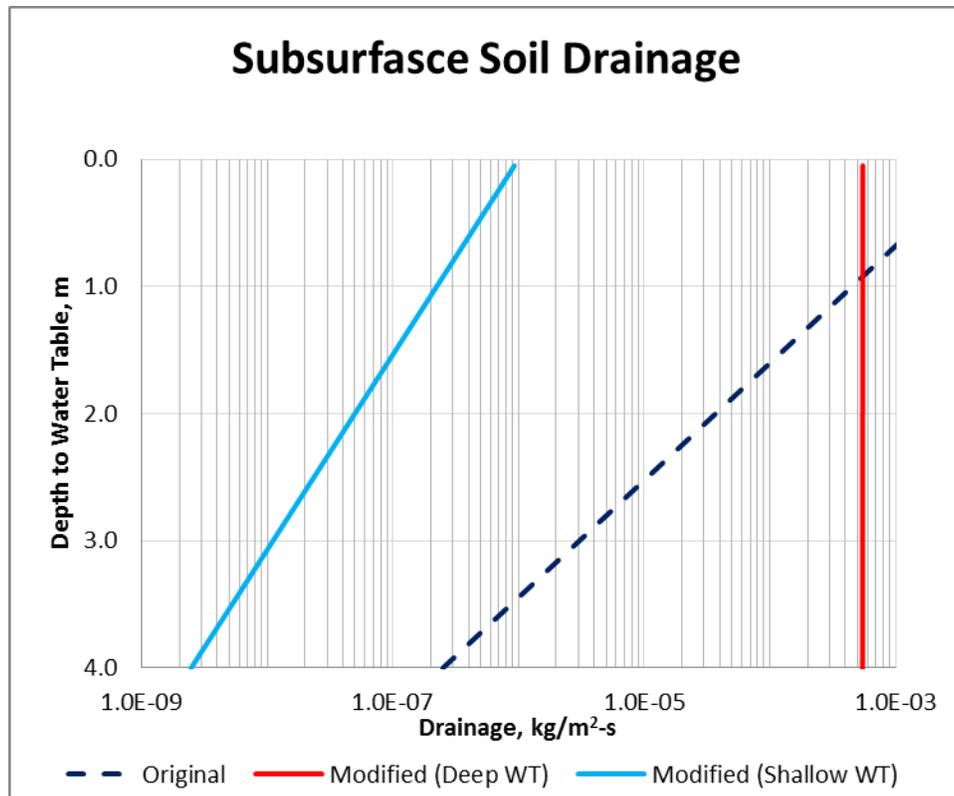


Figure 6. Subsurface Drainage as a Function of Water Table Depth with Original and Modified Subsurface Drainage Parameters.

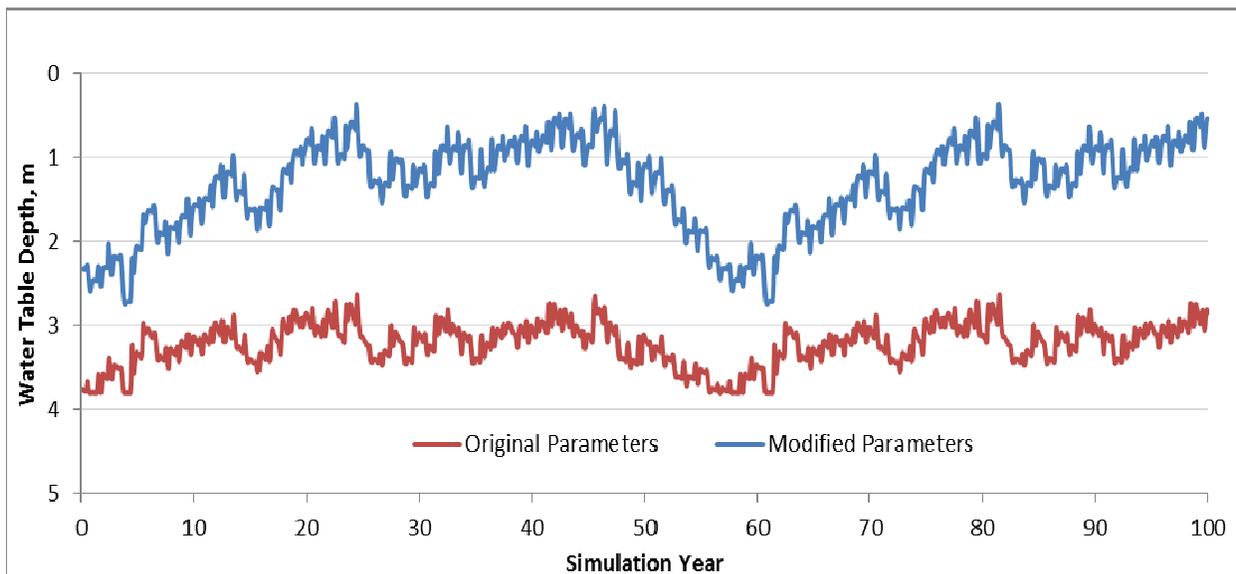


Figure 7. Water Table Depth with the Original and Modified (Shallow Water Table) Subsurface Drainage Parameters for Shallow Water Table Conditions (Fairbanks Grid Cell).

Table 6. Original and Modified Subsurface Drainage Parameters.

Subsurface drainage Parameters	Original Parameters	Modified Parameters	
		Shallow WT	Deep WT
$q_{\text{drai,max}}$ (kg/m ² -s)	5.50E-03	1.00E-06	5.50E-04
f_{drai} (1/m)	2.5	1.5	0.001

NOTE: WT is water table; subsurface drainage parameters are from Equation (2).

To test behavior in a dry and hot climate, we considered a grid cell located in Nevada with the water table located a few hundred meters below the ground. Using the modified drainage function (deep water table case) resulted in the fast drop in the water table to its maximum depth of 80 m (hard-wired in the code). However, this did not dry out the soil column - the changes in the soil moisture were insignificant compared to the original case. We could not achieve the dry soil profile in this case as well.

The reason for this was found to be in the way the bottom boundary condition in the soil moisture model is implemented in CLM. While the water table is located within the soil column, the bottom boundary condition is zero flux through the bottom of the soil column. When the water table drops below the soil column bottom (3.54 m), the lower boundary is moved half way between the water table and soil column bottom and fixed pressure and moisture are assigned to it. The fixed pressure and moisture preclude soils from drying out. This boundary condition should be modified to study the effects associated with the dry soils.

3.0 SENSITIVITY ANALYSIS RESULTS

Stand-alone CLM runs were performed for the base case and for each sensitivity analysis case. The base case in this study is the case with the original surface data extracted for the Fairbanks grid cell and the original rooting depth and subsurface runoff parameters defined in CLM. In each sensitivity case only one parameter was modified as described above, with the exception of one case. In this one case some of the most sensitive parameters were modified as discussed below to produce the largest possible impacts within the considered parameter constraints. The output parameters listed in Table 1 obtained for the base case were compared to the corresponding output parameters in the sensitivity analysis cases.

However, the outputs from the sensitivity runs were used to calculate the correlation coefficients for all the combinations between the major energy constituents and state variables. The average correlation coefficients for these combinations are shown in Figure 8. The box in this figure with subsurface drainage, infiltration and recharge refers to the soil model, which produces these output parameters.

The analysis of these results showed that some output parameters are highly correlated. This provided a basis for reducing parameter numbers. For example, the direct beam visible albedo, direct beam near-infrared albedo, diffuse visible albedo, and diffuse near-infrared albedo are highly correlated (0.99). So, only one of these 4 parameters was retained for the further analysis. The reference temperature (temperature at the 2 m height) and the ground temperature are highly correlated (0.95) as well. Ground temperature was retained for the further analysis.

As it can be seen from Figure 8, surface albedo has the greatest potential for impacting reference temperature (ground temperature) and relative humidity. The surface albedo is a function of vegetation and soil color.

Subsurface processes, such as subsurface drainage, infiltration and recharge, mostly impact the ground heat, and soil temperature. They have smaller impacts on reference temperature (ground temperature) and reference humidity.

Soil temperature, ground temperature, and reference humidity obtained from the sensitivity runs were compared to the base case values. These parameters are available as the average monthly values. The comparison was done with regard to the mean parameter values and mean difference between the parameter values during the simulation period (100 years). For the cases with the noticeable differences in the overall mean values, the comparisons were also done for the mean annual and seasonal (winter and summer) values.

The sensitivity cases that produced noticeable (greater than 0.5%) differences either between the mean soil temperatures or/and between ground temperatures were the cases related to the following parameters (Table 7):

- LAI (both, soil and ground temperature)

- SAI (both, soil and ground temperature)
- Shallow water table (soil temperature)

Both, the scarce vegetation case (LAIx0.5 and SAIx0.5) and shallow water table case lead to warmer soil and ground temperatures. To see the combined effects from these parameters, the sensitivity run in which all 3 parameters were modified (LAIx0.5, SAIx0.5 and shallow water table) was performed. The results of this case are shown in Table 7.

The sensitivity results are consistent with Figure 8. The vegetation parameters LAI and SAI have the greatest impact on surface albedo, which, in turn, impacts the soil and ground temperature. The other vegetation parameters are significantly less important. The surface albedo is also a function of soil color. However, the soil color has insignificant impacts. The shallow water table impacts the subsurface drainage, infiltration and recharge, and, thus, the soil temperatures.

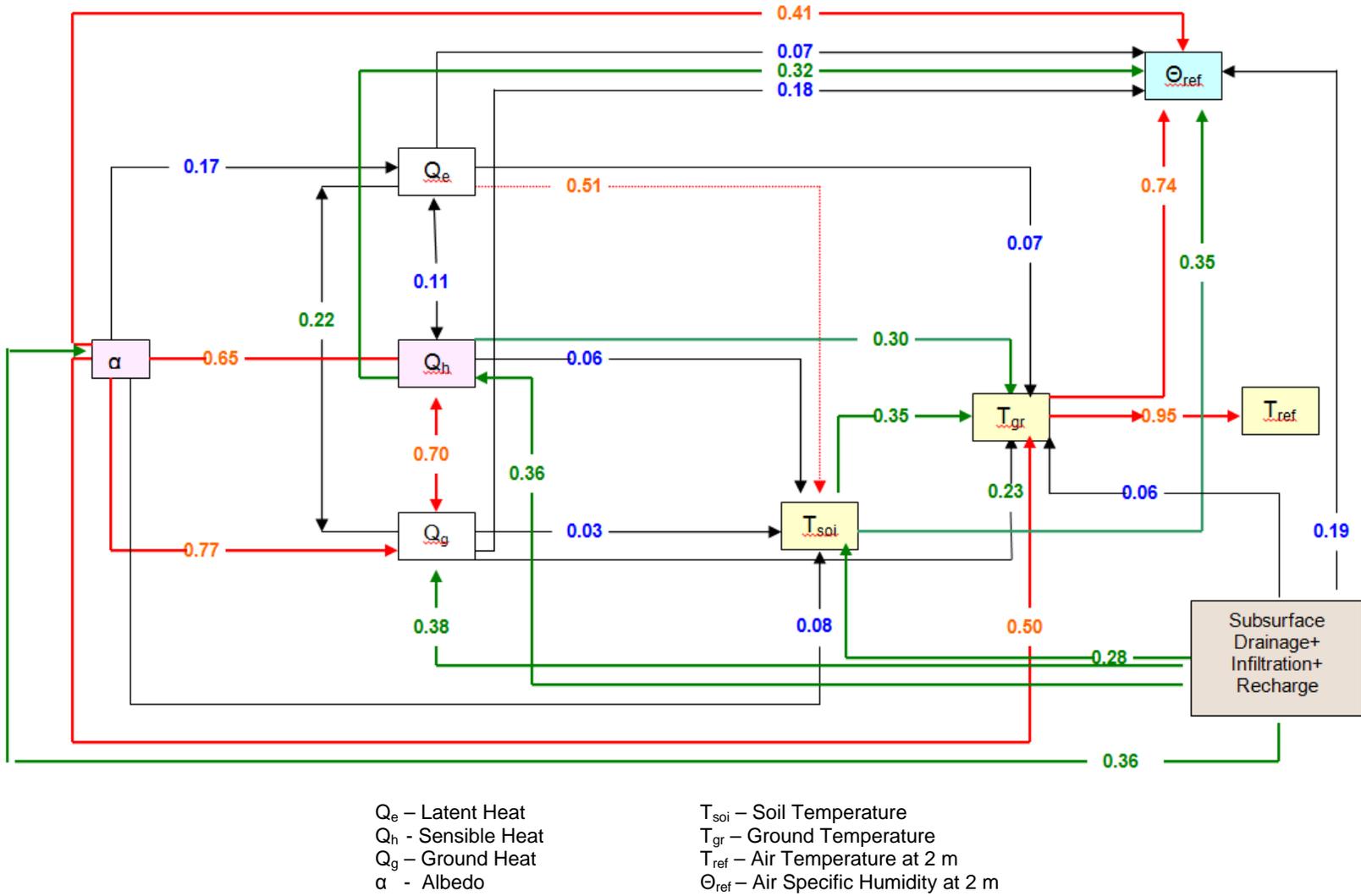


Figure 8. Correlation between the Energy Constituents and State Variables for the Fairbanks Grid Cell.

Note, that none of the sensitivity cases had any impact on the reference humidity. Based on Figure 8, the ground temperature is the major parameter that impacts the reference humidity. No change in reference humidity may indicate that the change in ground temperature was not sufficient.

Table 7. Comparison between the Base Case and Sensitivity Cases with the Greatest Impacts.

Sensitivity Case	Mean Ground Temperature (°C)	Mean Soil Temperature (°C)
Base Case	-7.87	-2.58
LAIx2	-8.37 (6.4%)	-3.02 (17.1%)
LAIx0.5	-7.68 (-2.4%)	-2.21 (-14.3%)
SAIx2	-7.94 (0.9%)	-2.36 (-8.5%)
SAIx0.5	-7.84 (-0.4%)	-2.63 (1.9%)
Shallow WT	-7.80 (-0.9%)	-1.51 (-41.5%)
LAIx0.5,SAIx0.5, and Shallow WT	-7.80 (-0.9%)	-1.42 (-45.0%)

NOTE: The numbers in parentheses show the percent change with regard to the base case values.

These results can be also explained based on the analysis of the net radiation (Q^*) partitioning at the land surface.

The net radiation at the land surface (Q^*) is partitioned between the ground heat (Q_g), sensible heat (Q_h), and latent heat (Q_e) as:

$$Q^* = Q_g + Q_e + Q_h \quad (3)$$

The distribution of the net radiation components in the base case is shown in Figure 9 (a). The sensible heat is the major component contributing 71.0% to the total. The latent heat is in second place contributing 25.8%, and the ground heat has the smallest contribution at 3.2%.

Figure 9 (b) provides a comparison between the different net radiation components obtained in the base case and in the two sensitivity cases: shallow water table and maximum LAI (or dense vegetation). As it can be seen from this figure, the sensitivity cases have predominantly impacted the ground heat. Because the ground heat is the smallest balance constituent in this environment, even noticeable changes in the ground heat have relatively small impact on the overall distribution of energy.

In case of the dense vegetation, the redistribution of energy is between the ground heat and sensible heat. In case of the shallow water table, the redistribution of energy is between the ground heat and latent heat.

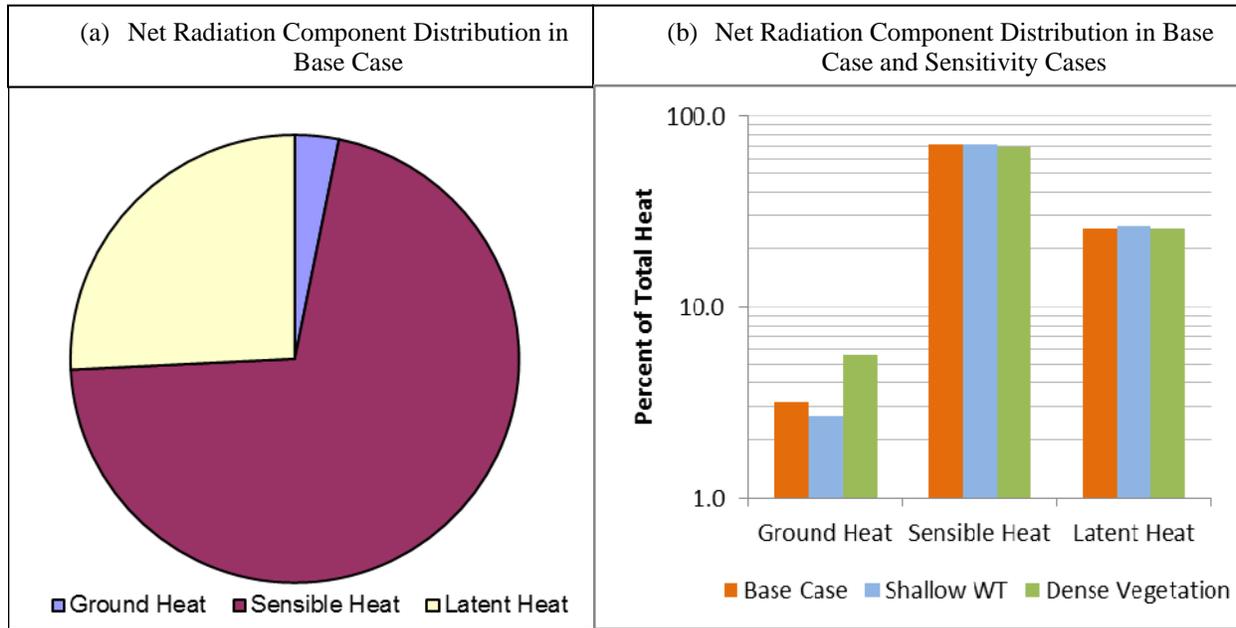
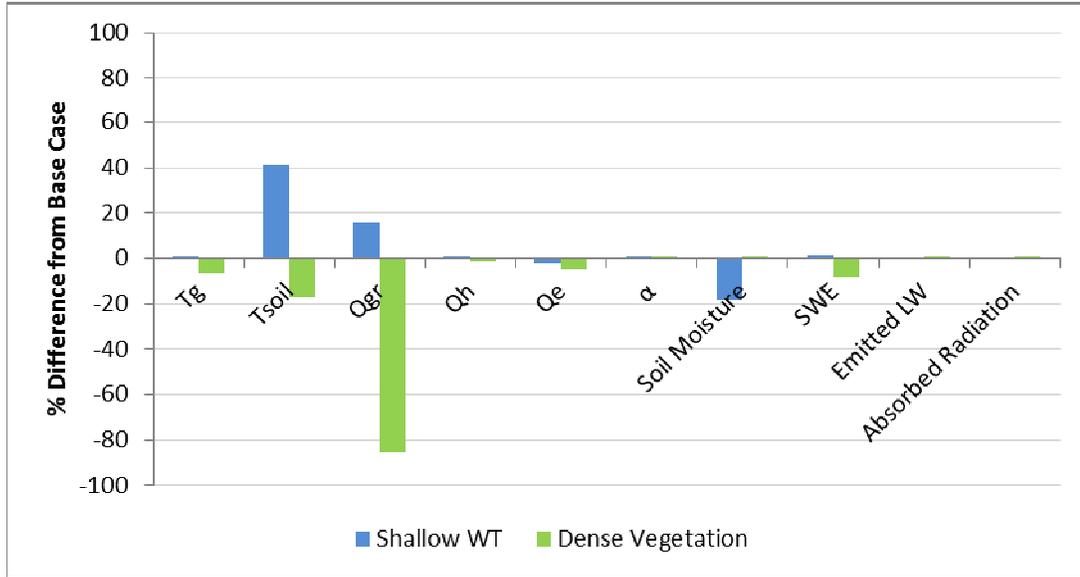


Figure 9. Net Radiation Components Comparison for the Fairbanks Grid Cell.

The effects of the vegetation and shallow water table are shown in Figure 10. The dense vegetation (maximum LAI case) affects average soil temperature (0.44°C lower than in the base case) and ground temperature (0.50°C lower than in the base case). The drop in temperatures is the result of less heat reaching the ground. Lower temperatures lead to greater snow accumulation (larger SWE).

The shallow water table affects soil temperature (1.07°C higher than in the base case) and soil moisture content (larger than in the base case). Increased soil moisture results in two changes. First, less heat is reflected from the ground. This is due to two factors – higher soil conductivity and lower albedo of saturated soils. Second, there is more evaporative (latent) heat because more water is available for evaporation. These changes have opposite effects - the first increases soil temperature and the second decreases soil temperature. The changes in ground heat are more important than the changes in the latent heat as evident from the temperature rise.

The effects of dense vegetation and shallow water table on the average annual and seasonal (winter and summer) soil and ground temperatures are shown in Figures 11 and 12.



NOTE: T_g is ground temperature, T_{soil} is soil temperature, Q_h is sensible heat, Q_e is latent heat, α is direct beam visible albedo, SWE is snow water equivalent, LW is longwave radiation.

Figure 10. Effects of Dense Vegetation and Shallow Water Table on the Average Values of the Energy Constituents and State Variables in Fairbanks Grid Cell.

As it can be seen from Figure 11, the effects of vegetation are significantly greater during the summer when LAI values are at their maximum values. The ground and soil temperatures are, on average, 0.88°C (ground) and 0.66°C (soil) lower in the summer in the dense vegetation case compared to the base case. They are, on average, 0.25°C (ground) and 0.28°C (soil) lower in the winter.

As it can be seen from Figure 12, the impacts of the shallow water table on the ground temperatures are small. The effects on the soil temperature (warming) are significant during the winter when the evaporation is low. The soil temperature is, on average, 2.78°C higher in the winter time in the shallow water table case compared to the base case. In some years the soil temperature is up to 5°C higher than in the base case. It is, on average, 0.51°C lower in the summer when the cooling from evaporation exceeds warming due to moist soil conditions.

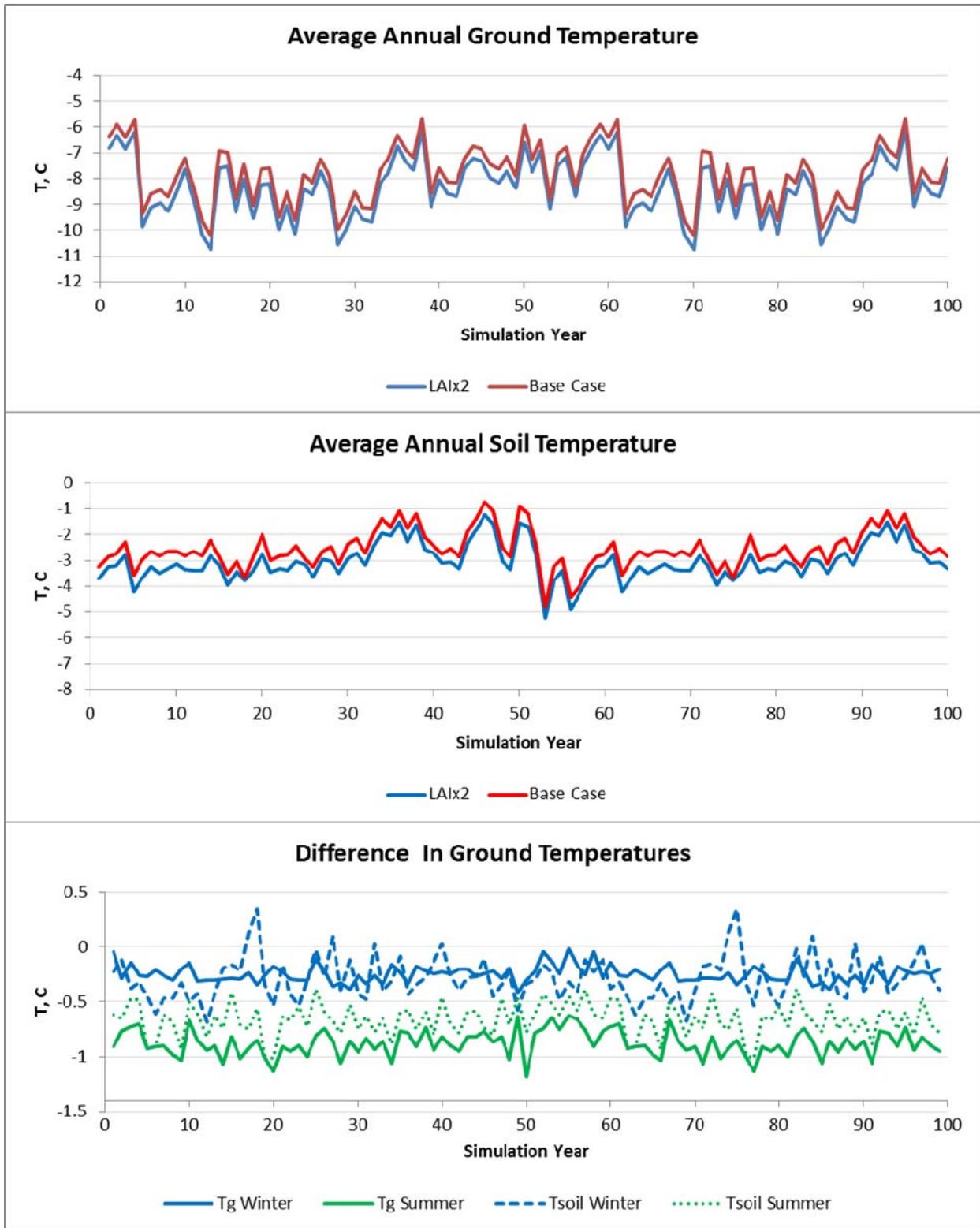


Figure 11. Effects of Dense Vegetation on the Average Annual and Seasonal Ground and Soil Temperatures in Fairbanks Grid Cell.

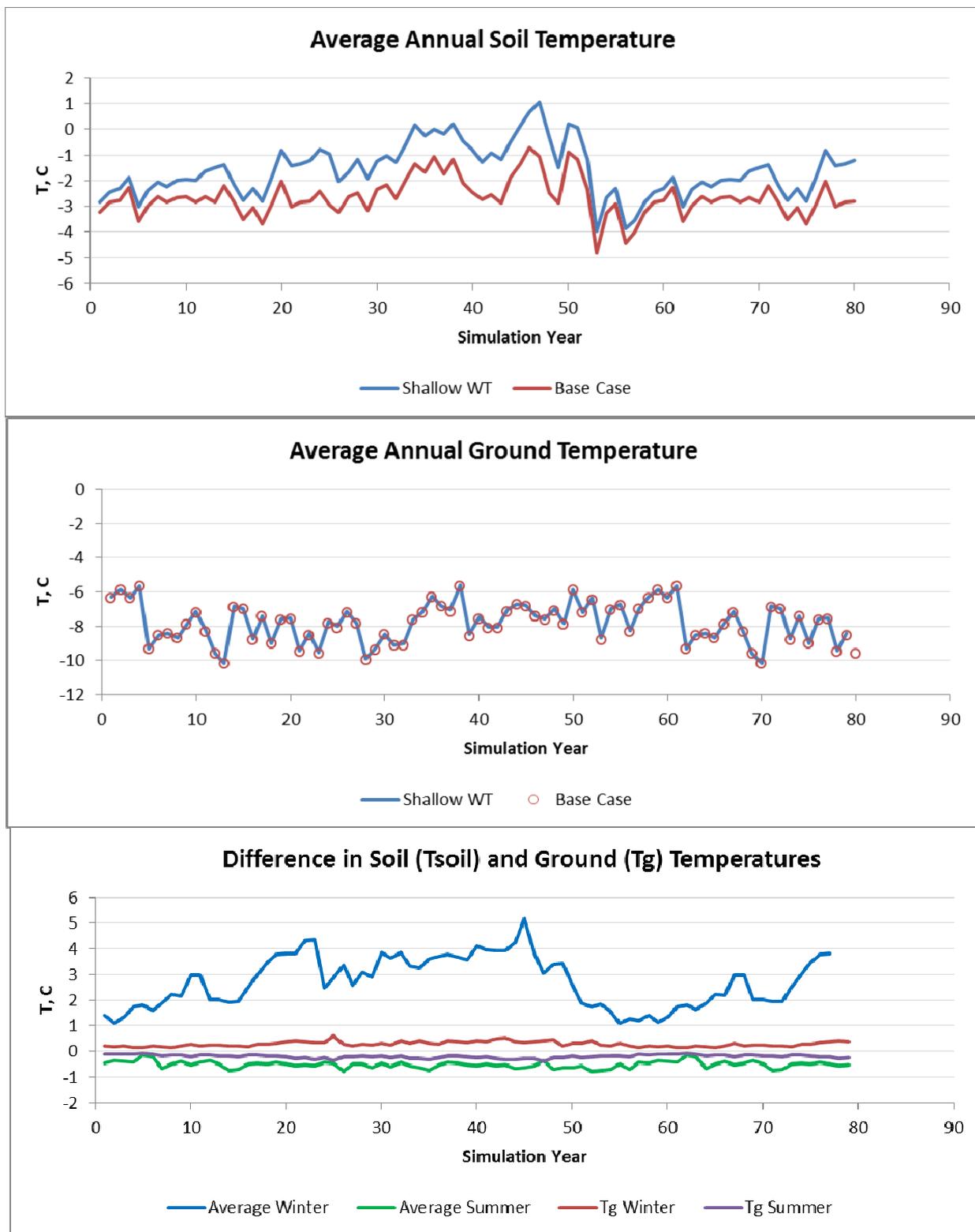


Figure 12. Effects of Shallow Water Table on the Average Annual and Seasonal Ground and Soil Temperatures for the Fairbanks Grid Cell.

Because the greatest impacts from vegetation occur in the summer and greatest impacts from the shallow water table occur in the winter, the combined impact from both, vegetation and shallow water table (LAIx0.5, SAIx0.5, and shallow water table case), is only slightly larger than the corresponding individual impacts.

Note that the vegetation parameter LAI (and to lesser extent SAI) has potential to impact the atmospheric model through its effects on the atmospheric temperature (correlated with ground temperature) and the ground heat. The effects due to natural variability considered in this analysis are moderate. However, larger effects might be expected when the vegetation is significantly changed due to either impacts (land management) or catastrophic event (fires).

As it was discussed above, soil moisture (shallow water table) has noticeable impact on the soil temperature, especially in the winter. However, its impacts on the ground temperatures are small. As a result, the short-term feedbacks to the atmospheric model are small as well.

While the short term effects of soil moisture are small, the long-term effects might be significantly larger. This is because the higher soil temperatures lead to greater thawing depths, which in turn may impact the permafrost condition and cause significant changes in the energy balance and corresponding feedback to the atmospheric model. These effects would take place over a significantly larger time scale than the considered simulation period of 100 years.

The effects of a shallow water table on the thawing depths are shown in Figure 13.

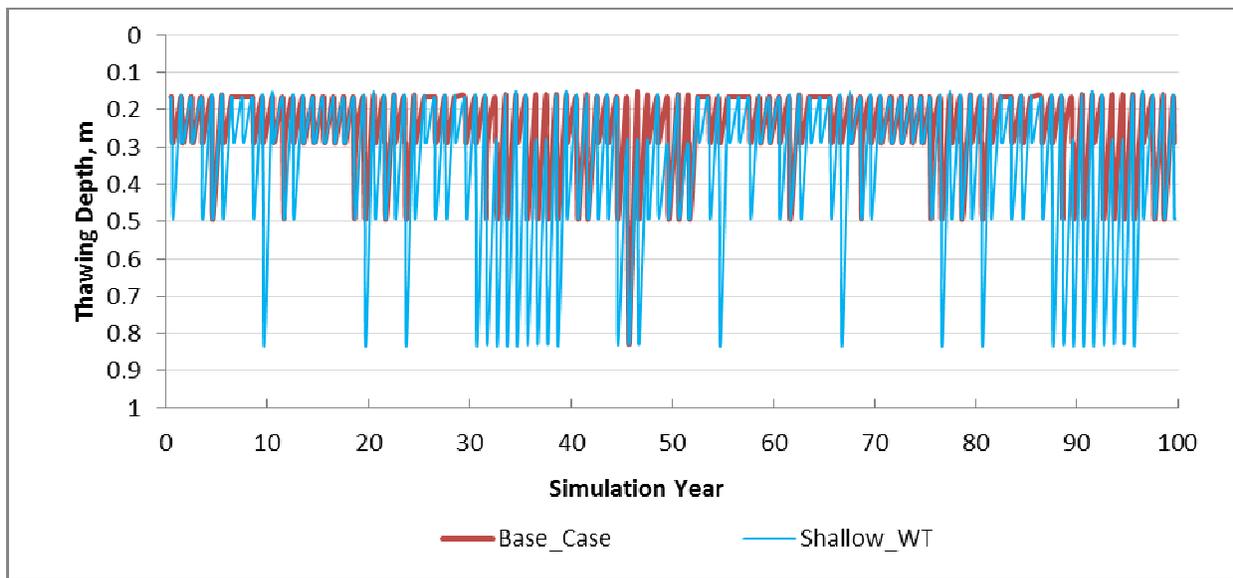


Figure 13. Effects of Shallow Water Table on Thawing Depth

There are a number of years during which the thawing depth under the shallow water table condition is greater than in the base case. The years in which this depth increases to 0.83 m are

the years in which the average soil temperature is at or above 0°C in the shallow water table case while it is below 0°C in the base case (Figure 12).

4.0 SUMMARY

The Community Land Model (CLM) simulates major physical processes at the land surface and in the shallow subsurface and calculates the parameters (including energy components) that are then used as the inputs to the atmospheric model. One of our goals was to identify the parameters that have greatest impacts on these inputs and thus, the greatest potential to impact the climate. Another goal was to identify the limitations in representing different physical processes and to determine whether these limitations restrict the ability of CLM to predict the distribution of energy at the land surface.

The focus of our analysis was on the arctic. We selected a grid cell near Fairbanks, Alaska and defined the ranges for all the applicable surface parameters in this grid cell. This included soil color, soil texture, and vegetation parameters. We modified the root distribution parameters hard-wired in CLM to represent its potential variability.

The major limitations of the CLM include the following:

- The soil depth is the same in any grid cell (3.54 m).
- The subsurface drainage parameters are hard-wired and are the same in any grid cell. These parameters keep the water table at a depth of 3 m and does not allow for large water table fluctuations.
- The bottom boundary condition in the soil moisture model does not allow for drying of the soil. As a result, the dry soils effects may not be properly evaluated.
- The aquifer is represented as an infinite source. This precludes the simulation of the water withdrawal impacts.
- The bottom boundary condition in the soil temperature model is zero flux. A better representation would be the actual temperature at the bottom of the bedrock.

We performed multiple sensitivity runs and analyzed the parameters that represent the direct inputs into the atmospheric model as well as the parameters that have indirect impacts on these inputs.

Beyond the parameter sensitivity analysis, we also explored changes to the mathematical representation of key physical processes. Specifically, we explored representation of the water table condition. We modified the subsurface drainage parameters to simulate these condition.

We reached the following conclusions based on this analysis:

- The vegetation and soil parameters mostly affect the ground heat component of the energy balance, which in this environment is only about 3% of the energy balance. As a result, these parameters have relatively small impacts on the atmospheric inputs.
- The most important parameters are the Leaf Area Index (LAI) and soil moisture. The other parameters have insignificant impacts on the energy distribution at the land surface.

- The vegetation affects both, soil and ground temperatures, with the most impacts occurring during the summer when the LAI are at their maximum values.
- The vegetation impacts ground temperature, which is highly correlated with the reference (atmospheric temperature). Because of this, the change in vegetation may impact the feedback into the atmospheric model and cause short-term changes in the climate.
- The soil moisture noticeably increases soil temperature during the winter when the evaporation is low and slightly decreases temperature in the summer when evaporation is high.
- Because soil temperature is weekly correlated with the ground temperature, the immediate impacts from the soil moisture are small. However, soil moisture may have significant long-term effects via its impacts on the depth of thawing.
- The combined effects of soil moisture and vegetation are only slightly higher than the corresponding individual effects because the greatest impacts from vegetation are in the summer and greatest impacts from soil moisture are in the winter.

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Sensitivity of the Community Land Model (CLM4.0) to Key Modeling Parameters and Modeling of Key Physical Processes with Focus on the Arctic Environment

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