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Parameter Sensitivity of the Arctic Biome–BGC Model for Estimating Evapotranspiration in the Arctic Coastal Plain

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Abstract

Previous research has indicated that modeling evapotranspiration (ET) in the Arctic Coastal Plain is challenging due to unique ecosystem conditions which include mosses, permafrost, and standing dead vegetation. A new version of the commonly used Biome–BGC (Biogeochemical Cycles) model (Arctic Biome–BGC) was developed that included: (1) a water storage and vertical drainage/infiltration routine that accounts for permafrost and mosses, (2) a modified representation of energy available at the surface which includes ground heat flux and simulates interception of incoming radiation by standing dead vegetation, and (3) a background evaporation routine that allows for moss and open water evaporation. In this study we investigated the sensitivity of model predictions to variations in parameter values, and to provide a conceptual validation of Arctic Biome–BGC. Using the generalized sensitivity analysis methodology, 13 parameters were evaluated. Results indicate that the model was sensitive to 8 of the 13 parameters. Seven of these parameters were introduced in the development of Arctic Biome–BGC and related to both energy reaching the ground surface and the amount of water stored within the soil and moss layers. The remaining sensitive parameter modulates the rate of snowmelt. These results validate the conceptual modifications included in the Arctic Biome–BGC model for estimating ET.

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Introduction

Evapotranspiration (ET) is a major component of the hydrological cycle and provides a key link between the water, energy, and carbon cycles in arctic ecosystems. Biome–BGC (Biogeochemical Cycles) is a widely used, ecosystem process model developed in mid-latitude regions designed to simulate the carbon, water, nitrogen, and energy cycles on a daily time step (Running, 1984; Running and Coughlan, 1988; Running and Gower, 1991; Hunt and Running, 1992; Thornton et al., 2002). The modeling approach is based on the assumption that differences in process rates between biomes are primarily a function of climate and general life-form characteristics (Kimball et al., 1997). The model has been evaluated in a variety of high-latitude ecosystems (>40°N) including boreal forests and tundra (Turner et al., 2006; Kimball et al., 2007; Bond-Lamberty et al., 2007, 2009).

While successful in some high-latitude environments, previous attempts to model ET in Arctic Coastal Plain ecosystems using Biome–BGC yielded unsatisfactory results (Engstrom et al., 2006). This failure was likely due to the failure of the model to represent processes associated with the unique conditions in Arctic Coastal Plain ecosystems, including non-vascular vegetation, permafrost, and standing dead vegetation. Arctic Biome–BGC was developed to be more suitable for arctic conditions and includes four major modifications: (1) a water storage/movement routine that accounts for permafrost and non-vascular vegetation (mosses), (2) a new representation of energy available at the surface that incorporates standing dead vegetation and ground heat flux, (3) a two-component background evaporation routine that simulates both moss and open water evaporation, and (4) substantial parameter changes in the sublimation and snowmelt routine (Fig. 1) (Engstrom et al., 2006). Predictions of ET at eddy flux tower sites using Arctic Biome–BGC significantly reduced the random and systematic errors compared to model predictions using Biome–BGC (Engstrom et al., 2006).

The Biome–BGC model requires a large number of parameters (over 30) to be set to undertake simulations (White et al., 2000). With the modifications made in the development of Arctic Biome–BGC an additional 11 parameters were introduced. In previous studies, the parameters for Biome–BGC were generally obtained from large-scale field data collection campaigns or from literature values (e.g., Kimball et al., 1997; Engstrom et al., 2006). Gathering the necessary parameters can be a difficult, time consuming, and expensive process even when working over small areas. Future work is expected to expand the Arctic Biome–BGC simulations to larger areas and the difficulty in obtaining parameter values only increases when model simulations are performed over large areas (White et al., 2000). Therefore, determining which parameters are most important may (1) reduce data collection needs, and (2) direct future research for simplifying the model and obtaining parameters over large areas.

Research Objectives

Sensitivity analysis enables a modeler to understand how the variation in the output of a model can be apportioned, quantitatively or qualitatively, to different sources of variation in model inputs (Saltelli, 2000). This includes providing information on the relative contribution of each of the input parameters to the model output (Saltelli, 2000). If the critical and redundant parameters can be identified, the focus of future research priorities and/or field data collection may be determined, and it may enable

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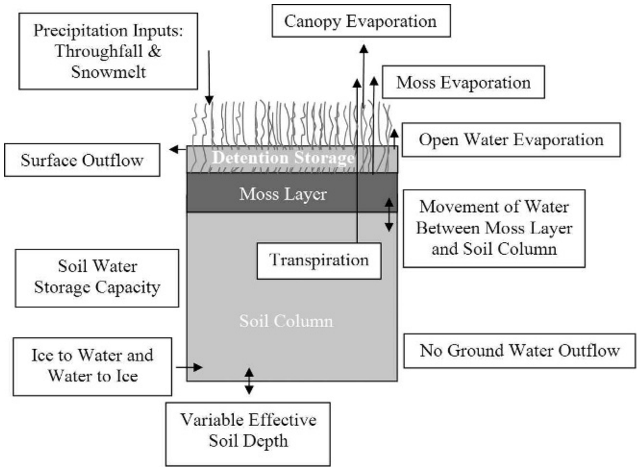

FIGURE 1. Conceptual representation of water inputs, outputs, storage, and movement within the soil, moss layer, and detention storage column in the Arctic Biome–BGC model.

a reduction in the number of required input parameters. This may be achieved by eliminating or using typical values for redundant parameters (Franks et al., 1997). This information can aid in determining if the model can be simplified for expansion to larger areas. Outputs from the sensitivity analysis provide an understanding of model behavior to determine if the model results are consistent with the modeler's conceptual understanding of the physical environment (Saltelli, 2000).

Previous sensitivity analyses of the Biome–BGC model have focused primarily on the processes controlling carbon fluxes and this is well documented (e.g.., White et al., 2000; Bond-Lamberty et al., 2007). Therefore, the purpose of this research was to determine the sensitivity of the model predictions of ET to the 11 parameters introduced or substantially changed in the development of the Arctic Biome–BGC model. The objectives were to (1) determine the relative importance of these parameters, and (2) provide a conceptual validation of the evapotranspiration portion of the Arctic Biome–BGC model.

Methods

STUDY AREA

The study area is located approximately 5 km east of the village of Barrow, Alaska (71°19′N, 156°37′W) within the Arctic Coastal Plain and encompasses an eddy flux tower (Fig. 2). The eddy flux tower is located within a drained thaw lake (Harazano et al., 2003). Mean annual temperature is approximately −12.1 °C. Average warm period temperature (June–August) is 3.0 °C (NCDC, 2010) with an average of 58.4 mm of precipitation (NCDC, 2010). Frequent fog and drizzle occurs in the study area due to its close proximity to the Arctic Ocean (approximately 0.5 km).

The study area is underlain with continuous permafrost and the average maximum depth of thaw is 0.37 m (Hinkel et al., 2001). The two soil types in the study area are *Typic Aquiturbels* and *Typic Molliturbels* (Michaelson and Ping, 2003). After snowmelt, the vegetation is completely flooded (Harazano et al., 2003) and the presence of permafrost leads to a water table that is at or near the surface throughout the growing season. The growing season is short, lasting from mid- to late June until the end of August or early September. The overstory of vascular vegetation is dominated by *Carex aquatilis* (Webber, 1978) and the understory, non-vascular vegetation, is comprised primarily of mosses including *Calliergon sarmenstosum*, *Pognatum alpinum*, *Polytrichum commune*, and *Dicranum elongatum* (Oechel and Sveinbjornsson, 1978). Mosses cover close to 100% of the study area (Miller et al., 1980). Additionally, there is a substantial amount of standing dead vascular vegetation that dies annually with a measured Leaf Area Index (LAI) of up to 1.23 (Dennis et al., 1978), similar to Gower and Kirschbaum (2008).

ARCTIC BIOME–BGC MODEL DESCRIPTION

This section provides a short overview of the modifications and parameters investigated within the Arctic Biome–BGC model in this study. For a more in-depth description, see Engstrom et al. (2006). The three major processes that impact ET that were modified in the development of Arctic Biome–BGC include (1) a water storage/movement routine that accounts for permafrost and non-vascular vegetation (mosses), (2) a surface evaporation routine that simulates both moss and open water evaporation and accounts for standing dead vegetation, and (3) the snowmelt and sublimation processes (Fig. 1).

Water Storage and Movement

Biome–BGC is similar to Arctic Biome–BGC in that it includes a 'bucket' model for water storage and movement (Fig. 1). Arctic Biome–BGC simulates surface detention storage,

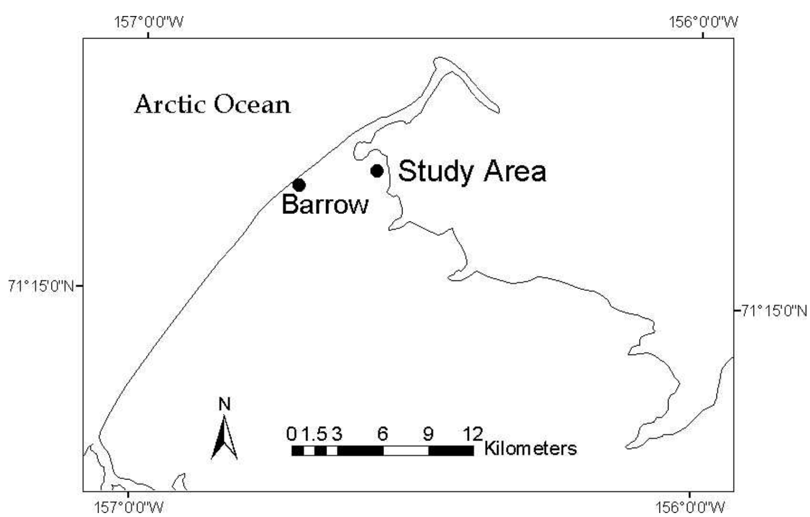

FIGURE 2. Location of the study site near the town of Barrow on the North Slope of Alaska.

time varying effective soil depth, and a moss layer at the top of the soil profile (Fig. 1). Detention storage capacity (DET-STOR-CAP) represents the amount of water that can be stored above the surface before runoff can occur. Due to the flat topography and/or microtopographic variations (i.e., troughs, low-centered polygons) in the landscape, water is stored above the surface after snowmelt or a period of heavy precipitation (Engstrom et al., 2005). Effective soil depth defines the soil depth for subsurface water storage. It is allowed to vary on a daily basis during the growing season (DOY [day of year] 147–273) in order to simulate changes in active layer depth (Engstrom et al., 2006). Effective soil depth is calculated using an empirical expression where the depth is varied as a function of time using the following fourth order polynomial: ($y = 1027.82 + -21.783x + 0.165x^2 + -0.000526x^3 + 0.0000006081x^4$; $r^2 = 0.985$). On the last day of the season, DOY 273, a step function sets the effective soil depth to zero. This end-of-season date was chosen because it corresponds well to the observed dates in the autumn when the active layer is refreezing in the Barrow region (Hinkel et al., 2001). The step function simulates the freezing of the active layer from both, the top and the bottom, towards the center (Hinkel et al., 2001), leading to an effective soil depth of zero (Engstrom et al., 2006).

The moss layer in Arctic Biome–BGC is conceptualized as an extension of the soil column using similar equations to the soil representation in Biome–BGC with parameter values representative of mosses. Mosses have unique hydraulic characteristics: high porosity and the ability to vertically transfer water to the surface via capillary flow (Oechel and Sveinbjornsson, 1978). Moss volumetric water content at field capacity ($M\theta_{fc}$) is calculated using moss parameter values in the Biome–BGC equation for soils below:

$$M\theta_{fc} = M\theta_{sat}\left(\frac{-0.015}{\psi_{msat}}\right)^{\frac{1}{m_b}} \tag{1}$$

where $M\theta_{sat}$ is the moss volumetric water content at saturation (M-VWC-SAT), −0.015 MPa is field capacity (Thornton, 1998), ψ_{msat} is the moss water potential at saturation (M-WP-SAT), and m_b (M-B) is an empirical shape parameter for mosses (Clapp and Hornberger, 1978).

Traditionally the amount of water that a soil can hold is calculated as a function of soil depth. This approach is not appropriate for mosses because measurements of moss water-holding capacity are generally reported as a function of their dry weight. Miller et al. (1978) provided measurements of moss water storage capacity (kg H_20 kg dry w^{-1}) relative to moss dry weight (kg dry w m^{-2}) for four moss species found in the Barrow region. We assumed that moss water storage capacity was analogous to the field capacity of soils. Utilizing this assumption moss water content at field capacity (MW_{fc}) was calculated using moss water storage capacity (M-FCM) and moss dry weight (M-DRY-W) (Miller et al., 1978).

The estimates for MW_{fc} and $M\theta_{fc}$ given above are used in the soil water equations for water content at both field capacity and saturation from Biome–BGC to estimate the water-holding capacity of the mosses. The equations from Biome–BGC used are

$$W_{fc} = 1000.0 d_{soil} \theta_{fc} \tag{2}$$

$$W_{sat} = 1000.0 d_{soil} \theta_{sat} \tag{3}$$

where W_{fc} and W_{sat} are the water content at field capacity and saturation (kg H_20 m^{-2} ground area) respectively, θ_{fc} is volumetric water content at field capacity, θ_{sat} is volumetric water content at saturation, and d_{soil} is the depth of soil (Thornton, 1998). Using the W_{fc} equation, the W_{fc} and θ_{fc} values are replaced by the moss equivalent values of MW_{fc} and $M\theta_{fc}$ and the equation is solved for d_{soil}. Once an estimate of d_{soil} is calculated, this value along with moss volumetric water content at saturation ($M\theta_{sat}$) are used to estimate moss water content at saturation (MW_{sat}). Vertical water movement in mosses (via capillary rise to the surface and down to the soil surface due to gravity) is simulated in Arctic Biome–BGC using the ratio of moss water content to moss field capacity. Therefore, the parameters which control the amount of water that can be stored in the mosses also impact the vertical movement of water in the soil-moss column.

Surface Evaporation

Surface (open water + moss) evaporation in Arctic Biome–BGC is simulated using a two-component, moss and open water, Penman-Monteith (PM) approach. When open water is present (i.e., water is held in the detention storage), surface resistance is zero. If water is within the moss layer, the surface resistance is calculated as a function of maximum moss conductance (MAX-M-COND). The MAX-M-COND is linearly reduced once the wet weight/dry weight ratio of the moss layer reaches a certain percentage (MW-COND-RED) to simulate the passive control of mosses to evaporation (Oechel and Sveinbjornsson, 1978). Boundary layer resistance (M-BLR) is set as a constant in the PM calculation and is derived from observed values in moss-covered environments (Miller et al., 1978).

Arctic Biome–BGC includes a standing dead LAI parameter (DEAD-LAI). This parameter simulates the large amount of standing dead vegetation present in the landscape. The standing dead vegetation intercepts a substantial amount of incoming shortwave radiation reaching the surface, especially early in the season (Dennis et al., 1978). It is assumed that the amount of radiation absorbed by the standing dead LAI is analogous to a similar amount of green LAI. DEAD-LAI is set as a fixed input parameter (Engstrom et al., 2006).

Snowmelt and Sublimation

Errors in simulated snowmelt date have been found to impact Arctic Biome–BGC ET estimates (Engstrom et al., 2006). The snowmelt routine in Arctic Biome–BGC is unchanged from the original Biome–BGC model. There are two parameters, snow absorptivity (1 – albedo) (SN-ABS) and temperature coefficient (TCOEF), that control snowmelt in the model. The SN-ABS parameter influences the rate at which radiation impacts sublimation and snowmelt. The second parameter, TCOEF, controls the snowmelt process only when air temperature is above zero degrees Celsius (Coughlan, 1991). When the air temperature is below zero degrees Celsius, the model assumes that snowmelt is a radiation-driven process and the simulated snowmelt date would be controlled by the SN-ABS parameter.

GENERALIZED SENSITIVITY ANALYSIS

There are two broad approaches to perform a sensitivity analysis, local (deterministic) and global (stochastic) (Kala, 2005). Local sensitivity analysis is the most commonly used approach where the behavior of the model is evaluated by allowing parameters to vary fractionally around the nominal values (Saltelli, 2000). This approach has been used to investigate the sensitivity of the Biome–BGC model when simulating net primary production (White et al., 2000). Local sensitivity analysis approaches are limited because they typically evaluate only in the parameter space near the best estimate parameter set. This allows for a very narrow estimate of model sensitivity (Beven, 2001).

A global sensitivity analysis approach allows for searching a larger portion of parameter space and may give a more useful estimate of the importance of a parameter within the model structure (Beven, 2001). A range in parameter values is investigated in a global sensitivity analysis with all of the inputs varied simultaneously (Saltelli, 2000). There are a number of global sensitivity analysis approaches. One approach that makes minimal assumptions about the shapes of the parameter surface (and is essentially a non-parametric method) is the generalized sensitivity analysis (GSA) (Hornberger and Spear, 1981; Beven, 2001).

The GSA approach is based on Monte Carlo sampling of the parameter space to obtain multiple randomly selected parameter sets. Parameter sets are compiled by randomly selecting each of the individual parameters from a uniform distribution across a specified range selected to represent the feasible range of values for the specified model application. The Monte Carlo sampling draws parameter combinations for model simulations from the entire parameter space. The relative performance of each parameter set is evaluated using a likelihood measure (performance index) based on the difference between calculated and observed ET.

In the GSA approach, the model simulations are separated into sets that are considered behavioral (acceptable) and non-behavioral (unacceptable) based on the selected performance measure (likelihood) with a defined threshold set to partition the model simulations (Beven, 2001). The difference in the distribution of each individual parameter value between the behavioral and non-behavioral parameter sets is then evaluated by comparing the cumulative distribution function (CDF) across the specified parameter range. A straight line would represent a uniform distribution and an insensitive parameter while a large departure from a straight line would represent a non-uniform distribution, indicating a sensitive parameter (Franks et al., 1997).

A quantitative assessment of the differences in the behavioral and non-behavioral parameter distributions can be calculated using the non-parametric Kolmogrov-Smirnov (KS) d-statistic (Beven, 2001). The d-statistic represents the maximum vertical distance between a pair of CDFs (Beven, 2001; Makino et al., 2001). While the test statistic may not be robust for a large number of simulations, relative sensitivity may be assessed by grouping parameters into low ($p \geq 0.100$), medium ($0.010 < p < 0.100$), and high sensitivity ($p \leq 0.010$) classes on the basis of their associated p-values (Madsen, 2000).

MODEL INPUT DATA AND INITIAL CONDITIONS

In order to perform model simulations, daily inputs of surface meteorological variables, a suite of ecophysiological constants, site characteristic values, and a model spinup are needed. The required surface weather inputs include precipitation, minimum and maximum temperature, daytime temperature, daily average vapor pressure deficit, day length, incoming shortwave radiation, and ground heat flux. Daily surface weather inputs for model simulations and spinup (described below) were obtained from the National Weather Service Station (NWS) at the W. Wiley Airport, the eddy flux tower site, and from the MT CLIM model (Thornton et al., 2000). Daily precipitation data were corrected for gauge under-catch and trace estimates using the approach of Yang et al. (1998). For a complete description of the surface weather inputs used and the ecophysiological constants and site characteristic values that were held constant within the sensitivity analysis, see Engstrom et al. (2006).

The model uses a spinup routine to bring the model into a steady state with respect to the site climate and the specified vegetation ecophysiology (Thornton et al., 2002). This steady state sets the initial conditions of plant and soil pools of carbon and nitrogen which may impact model estimates of vegetation growth and, in turn, ET through soil-vegetation-water interactions. In order to isolate model variability due to parameter uncertainty, the impacts of the initial conditions need to be minimized. Therefore, the initial conditions and an additional 5 years of simulations were run prior to comparing observed to estimated ET values in the Monte Carlo simulation. The additional 5 years of simulations were run to ensure that the model states were stable (i.e., did not run out of water and kill the vegetation) in a range of precipitation and temperature conditions.

OBSERVED ET DATA

Observed 30 minute latent heat flux data were obtained from an eddy flux tower at a height of 1.9 m above ground level, over a 4 year period from 1999 to 2002. The tower was operational during the growing season from DOY 153 to 247 for all 4 years. The half hourly latent heat flux (LE) data were converted to water units and then summed to obtain a daily ET total, in mm/day. For more information on the flux data, see Harazano et al. (2003).

Monte Carlo Simulation

Model simulations were made over 4 years, 1999–2002, using a total of 50,000 parameter sets. For each of the model runs, the parameter set was determined by randomly selecting individual parameter values from a uniform distribution across the specified ranges of 12 of the 13 parameter values (Table 1). The specified ranges for each of the 12 parameters were determined using data from field observations or published values (Table 1). In the model, soil depth is simulated using a fourth-order polynomial equation. Therefore, variations in soil depth within the sensitivity analysis were achieved using a multiplier (E-SOIL-MULT) to increase/decrease the depth values by a constant fraction every day. The multiplier was set to represent the range of depth of active layer observations at the study site (Engstrom et al., 2006).

Model performance for each parameter set was quantified using the coefficient of efficiency (E). The E value is an objective function widely used to evaluate the accuracy of both the magnitude and timing of model estimates (e.g. Anderson et al. [2001]; Beven [2001]). The coefficient of efficiency is defined as:

$$E = \frac{\sum_{i=1}^{n} \left(O_i - \overline{O}\right)^2 - \sum_{i=1}^{n} \left(E_i - O_i\right)^2}{\sum_{i=1}^{n} \left(O_i - \overline{O}\right)^2} \qquad (4)$$

where n is the number of observations, E_i and O_i are the estimated and observed ET values, respectively, for ith day, and $\overline{O}$ is the average observed ET.

Results

Only model runs with $E > 0$ were used in this study since a value less than this threshold represents a model where the mean ET for the period is a better predictor than the simulation values. A total of 25,364 of the 50,000 model runs were above this threshold. Model simulations where then ranked by E, and the top 1000 and bottom 1000 simulations were selected as the behavioral

TABLE 1

Parameter ranges for each of the 13 parameters used in the sensitivity analysis.

Parameter	Range		Units	Source
Moss Field Capacity Multiplier (*M-FCM*)	10	93	g H_2O/g dry weight	Miller et al. (1978)
Moss Dry Weight (*M-DRY-W*)	0.008	0.244	kg/m^2	Webber (1978)
Moss Volumetric Water Content at Saturation (*M-VWC-SAT*)	0.7	0.95	Unitless	Beringer et al. (2001)
Moss Clapp-Hornberger b (*M-B*)	−0.5	−4	Unitless	Beringer et al. (2001)
Moss water potential at Saturation (*M-WP-SAT*)	−0.00083	−0.00118	MPa	Beringer et al. (2001)
Moss water % Dry Weight at Start of Conductance Reduction (*MW-COND-RED*)	200	400	% dry wt.	Miller et al. (1978)
Maximum Moss Conductance (*MAX-M-COND*)	0.077	0.1	m/s	Miller et al. (1978)
Moss boundary layer resistance (*M-BLR*)	90	130	s/m	Miller et al. (1978)
Dead LAI (*DEAD-LAI*)	0.5	1.5	Unitless	Bigfoot Data
Detention Storage Capacity (*DET-STOR-CAP*)	0	50	kg/m^2	Fernandes (1999); Ivanov (1981)
Effective soil depth multiplier (*E-SOIL-MULT*)	0.77	1.23	Unitless	This Study
Snowmelt Temperature Coefficient (*TCOEF*)	0.65	2.7	kg/m^2 °C/d	Kane et al. (1997); Coughlan (1991)
Snow Absorptivity (*SN-ABS*)	0.07	0.2	Unitless	Dingman et al. (1980)

and non-behavioral model simulations, respectively. The CDFs for the behavioral and non-behavioral model simulations were plotted for each individual parameter (Fig. 3). There is a large range in the magnitude of separation between the behavioral and non-behavioral CDFs for the individual parameters (Fig. 3). This indicates there is substantial range in the relative sensitivity of the individual parameters.

The KS d-statistic values for each of the parameters investigated are given in Table 2. Eight of the parameters were categorized in the high sensitivity class. These parameters ranked from the highest to lowest values are: (1) DEAD-LAI, (2) SN-ABS, (3) M-B, (4) M-BLR, (5) M-DRY-W, (6) DET-STOR-CAP, (7) M-FCM, and (8) E-SOIL-MULT (Table 2). Three parameters fall in the medium sensitivity class, (1) M-WP-SAT, (2) TCOEF, and (3) MAX-M-COND. Two parameters fall in the low sensitivity class, MW-COND-RED and M-VWC-SAT (Table 2). Discussion of the sensitivity of the individual parameters will be made within groups according to their role in regulating the ET. These groups are (1) water storage and movement, (2) surface evaporation, and (3) snowmelt and sublimation.

WATER STORAGE AND MOVEMENT

Water storage and movement is controlled by seven parameters, DET-STOR-CAP, M-DRY-W, M-B, M-FCM, E-SOIL-MULT, M-WP-SAT, and M-VWC-SAT. Together, these parameters control the total amount of water stored in the Arctic Biome–BGC 'bucket' and the horizontal and vertical movement of water. Five of these parameters are in the highly sensitive category including DET-STOR-CAP, M-DRY-W, M-B, M-FCM, and E-SOIL-MULT (Table 2). DET-STOR-CAP controls multiple processes that impact ET estimates: (1) the total amount of water that may be stored within the bucket, (2) whether background evaporation is from open water or mosses, and (3) when water runs off and leaves the bucket. The next three highly sensitive parameters, M-DRY-W, M-B, and M-FCM, control the water storage capacity of the mosses. Water storage capacity of the mosses also influences the amount of simulated capillary rise. The rate of capillary rise may limit the daily ET rates from the surface, when the only source of water for moss evaporation is from the soil surface (i.e., no precipitation inputs). The final, highly sensitive water storage and movement parameter was E-SOIL-MULT. This parameter represents variations in active layer depth and indicates that the amount of water that can be stored within the soil influences the model ET estimates.

The remaining parameters that control water storage and movement were M-WP-SAT and M-VWC-SAT. Based on their KS d-statistic, *p*-values for these parameters were grouped into the medium and low sensitivity classes (Table 2). For both of these parameters there was very little difference between the CDFs of the behavioral and non-behavioral simulations (Fig. 3, e and h). This indicates that the model outputs were not sensitive to these parameters for the meteorological forcing set at this site.

SURFACE EVAPORATION

Four of the parameters investigated impact the rates of surface evaporation. These are DEAD-LAI, M-BLR, MAX-MOSS-COND, and MOSS-COND-RED. The CDF of the DEAD-LAI values from the behavioral model predictions cover a small portion of the parameter range close to the value 1.0. The non-behavioral predictions cover the entire parameter range (Fig. 3, b). This indicates that the model is particularly sensitive to this parameter, and the optimum DEAD-LAI parameter value was around 1.0. The model predictions are also very sensitive to the M-BLR parameter. This parameter accounts for atmospheric resistance in the background evaporation routine and influences the maximum rate of daily evaporation from the background surface. This limits ET rates early in the season when water and available energy are not limiting factors. MAX-MOSS-E and MOSS-COND-RED also influence the daily rates of evaporation from the background surface by reducing moss evaporation when water is a limiting factor. The model is not sensitive to these parameters.

SNOWMELT AND SUBLIMATION

Two parameters control the snow dynamics of the hydrologic cycle: SN-ABS and TCOEF. SN-ABS is the second most sensitive parameter to the model ET estimates (Table 2). The SN-ABS parameter influences both sublimation and snowmelt when air temperature is below 0 °C, and radiation is the primary driver of the processes. When the air temperature is above 0 °C the TCOEF parameter controls the snowmelt process. TCOEF was categorized into the medium sensitivity group.

→

FIGURE 3. Cumulative distribution functions (CDF) of the behavioral and non-behavioral simulations of the 13 individual parameters varied in the Monte Carlo simulation. The parameter abbreviations are defined in the text.

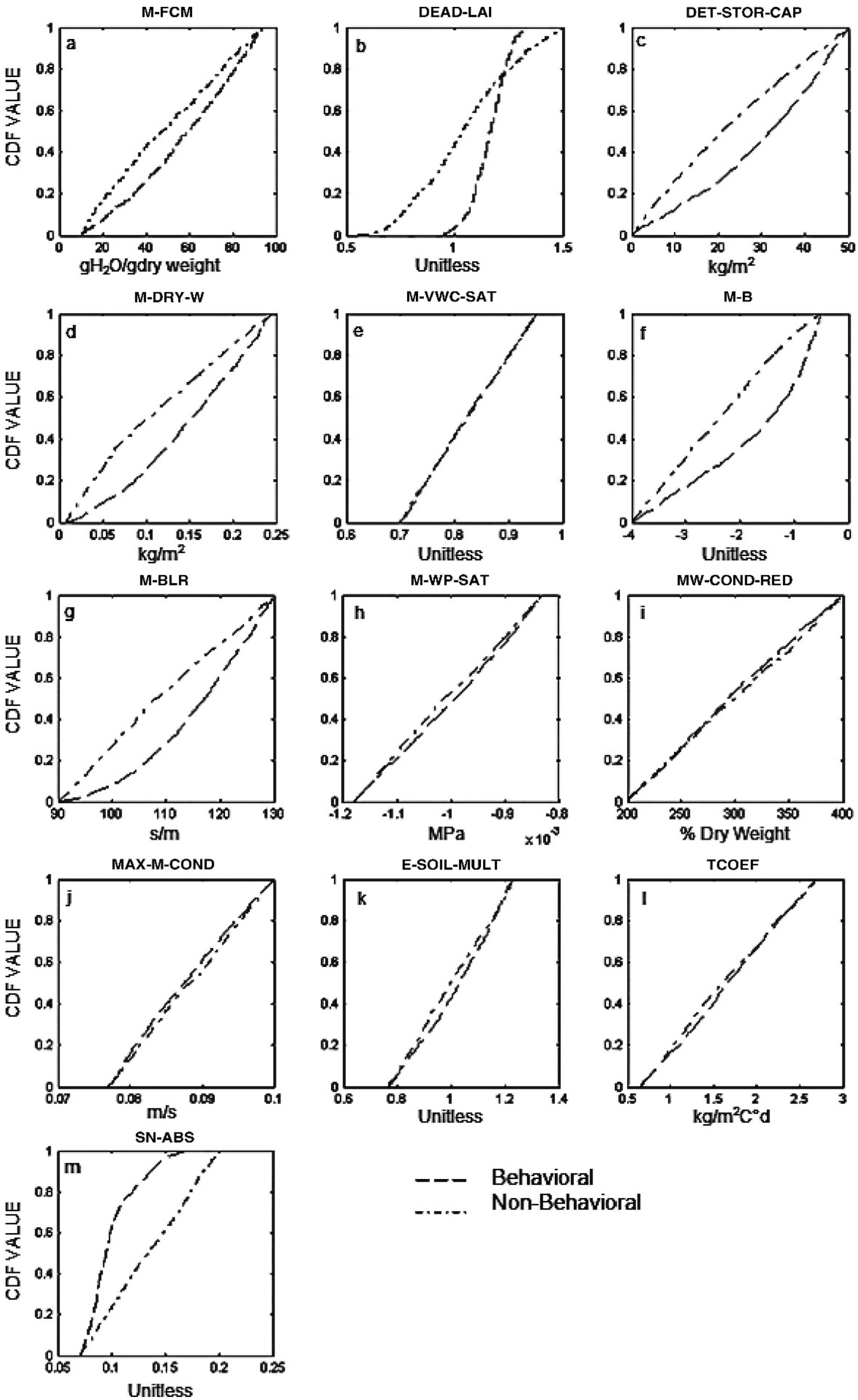
M-FCM
a
CDF VALUE
gH2O/gdry weight
DEAD-LAI
b
Unitless
DET-STOR-CAP
c
kg/m2
M-DRY-W
d
CDF VALUE
kg/m2
M-VWC-SAT
e
Unitless
M-B
f
Unitless
M-BLR
g
CDF VALUE
s/m
M-WP-SAT
h
MPa
x10-3
MW-COND-RED
i
% Dry Weight
MAX-M-COND
j
CDF VALUE
m/s
E-SOIL-MULT
k
Unitless
TCOEF
l
kg/m2C°d
SN-ABS
m
CDF VALUE
Unitless
Behavioral
Non-Behavioral

TABLE 2

Kolmogorov-Smirnov d-statistic, probability values, relative sensitivity, and process impacted for all 13 parameters. Parameter abbreviations are defined in the text.

Parameter	d-statistic*	*p*-value*	Relative Sensitivity	Process Impacted
DEAD-LAI	**0.442**	**0.000**	High	Surface Evaporation
SN-ABS	**0.437**	**0.000**	High	Snowmelt
M-B	**0.294**	**0.000**	High	Water Storage
M-BLR	**0.27**	**0.000**	High	Surface Evaporation
M-DRY-W	**0.255**	**0.000**	High	Water Storage
DET-STOR-CAP	**0.239**	**0.000**	High	Water Storage
M-FCM	**0.167**	**0.000**	High	Water Storage
E-SOIL-MULT	**0.084**	**0.002**	High	Water Storage
M-WP-SAT	0.061	0.046	Medium	Water Storage
TCOEF	0.059	0.059	Medium	Snowmelt
MAX-M-COND	0.056	0.084	Medium	Surface Evaporation
MW-COND-RED	0.042	0.334	Low	Surface Evaporation
M-VWC-SAT	0.025	0.910	Low	Water Storage

* Numbers in bold type indicate ''highly sensitive'' parameters.

Discussion

Results of the sensitivity analysis confirmed that all three of the processes modified in the creation of Arctic BIOME BGC impact ET estimates. This provides a conceptual validation for the changes made in the development of Arctic Biome–BGC model because these processes ([1] energy available at the surface, [2] timing of snowmelt, and [3] total water storage and water movement within the simulated bucket) were expected to be the most important for controlling ET in Arctic Coastal Plain environments (Engstrom et al., 2006). Overall, the primary driver of ET is energy available at the surface with atmospheric and water availability having less control. However, water storage and movement becomes crucial for properly simulating ET for the entire season. This is due to ET being greater than incoming precipitation during the snow-free period, and the fact that water must be stored within the system for evaporation late in the season. Over 24,000 model runs were eliminated in this study because they had an efficiency value below zero. Many of these model runs were characterized by water storage being depleted late in the season.

WATER STORAGE AND MOVEMENT

Water in the Arctic Biome–BGC 'bucket' can be stored in one of three categories: detention storage, moss water storage, and soil water. Five of the seven parameters that control water storage in the 'bucket' fall in the highly sensitive category: DET-STOR-CAP, M-DRY-W, M-B, M-FCM, E-SOIL-MULT (Table 4). This indicates that properly modeling water storage within the model is very important for accurately simulating ET rates. While highly sensitive, the CDFs of these five parameters cover a much larger range in parameter space (Fig. 3, a, c, d, f, and k) relative to the DEAD-LAI and SN-ABS parameters (Fig. 3, b and m). This indicates that, while the model is sensitive to these parameters, a wider range of values may produce a good fit to the observations. The wider range in values may be due to the large number of parameters needed to simulate the model representation of water movement and storage within the model. While the model uses a simple, bucket-type water storage and movement approach, there are still a large number of parameters needed in order to estimate the available store of water. This allows for the interaction between the different parameter combinations to simulate the appropriate water storage capacity (moss, detention, and soil), and still produce acceptable estimates of ET.

The soil water storage routine in this model uses a simple bucket approach that does not consider lateral subsurface water movement. There is substantial variability in surface moisture across the Arctic Coastal Plain (Engstrom et al., 2005, 2008) which may lead to different evaporation rates (Mendez et al., 1998; Vourlitis and Oechel, 1997). While spatial heterogeneity in soil moisture may be important, representing this within the model would require a laterally distributed subsurface water routine. This would significantly increase the number of parameters needed and the overall complexity of the model. This addition would likely lead to a large degree of parameter uncertainty within the model and move away from the underlying simple model philosophy that Biome–BGC was built on.

SURFACE EVAPORATION

The primary driver of surface evaporation rates is the DEAD-LAI parameter. This parameter impacts the amount of incoming shortwave radiation intercepted before it reaches the background surface. At this site, the dominant source of the total ET is from the background (i.e., open water if water is in the detention storage layer or the mosses) and the available energy is the primary driver of the background evaporation rates (Engstrom et al., 2006). It follows that the model would be sensitive to an important controller of energy reaching the background surface in simulating ET at this site.

Model outputs were not sensitive to parameters that controlled reductions in ET associated with water limitations. The lack of sensitivity to these parameters at this site is not surprising because of the large amount of available water in the study area (Engstrom et al., 2005). While the model is not sensitive to these parameters at this site, the parameters may be important for simulating ET in drier areas of the Arctic Coastal Plain, during seasons with longer dry periods, or if the snow-free season length increases in a changing climate.

SNOWMELT AND SUBLIMATION

Snow cover is the dominant portion of the hydrologic cycle in the arctic environment. The annual snow cycle is characterized by a relatively long accumulation period (8–9 months), followed by a brief snowmelt period (10–14 days) (Kane et al., 1997). While the snowmelt period is brief, the date of snow disappearance can vary by up to a month from year to year (Kane et al., 1997). Precise estimates of snowmelt dates are crucial for predicting ET (1) because of the large albedo differences between snow and tundra vegetation, (2) because of its impact on season length, and (3) for establishing the initial conditions for the summer water balance. The importance of simulating the snowmelt process in the model is reflected in the high sensitivity of the SN-ABS and the medium sensitivity of the TCOEF parameters. Due to the lower model sensitivity of the TCOEF relative to the SN-ABS parameter, it appears that radiation and not temperature is the primary driver of modeled snowmelt and sublimation rates.

Summary and Conclusion

There is a large range in the sensitivity of the Arctic Biome–BGC model estimates of ET to the 13 parameters investigated. Eight of the parameters were classified into the high sensitivity category, while the remaining five parameters were grouped into the moderate to low sensitivity classes. This indicates that future research for model simulations made using Arctic Biome–BGC at wet sites should focus on the eight highly sensitive parameters and the remainder can be set at average/nominal values (Franks et al., 1997). Furthermore, a sensitivity analysis of all parameters at a drier site is needed to determine whether the same parameters are highly sensitive when water availability is more important in controlling ET (Franks et al., 1997). Over small areas such as the one investigated, field-based measurements may be used, but expanding to large areas in the Arctic may be difficult due to limits in data availability (Kane et al., 1990). Remote sensing may provide some input data for regional applications of this model. For example, the non-photosynthetic vegetation component from spectral mixture analysis may provide the input for dead LAI over large areas and high resolution digital elevation models (e.g. IFSAR data) may allow for the estimate of detention storage capacity across wide areas of the Arctic Coastal Plain.

Each of the three major modifications made in Arctic Biome–BGC had at least one parameter fall in the highly sensitive category. This provides a confirmation that these processes are important for simulating ET in arctic ecosystems and provides a conceptual validation for the model. In terms of the bucket portion of the model, there was a substantial range in the parameters that controlled moss water storage and movement. In future research, a simplification of the moss storage capacity may increase model sensitivity to these values and reduce model uncertainty. However, such a simplification may remove the physical significance of the parameters used in this study and the ability to compare the values to field measurements.

While this study only looks at one model at a single site, it does indicate that representing the unique conditions of arctic environments is important for properly simulating ET. Processes such as snowmelt, moss water movement and evaporation, depth of active layer, and ground heat flux are important when simulating ET in arctic environments. Even though a model such as Biome–BGC may work very well in mid-latitude environments, these unique arctic processes violate assumptions that are made within the model (i.e., zero ground heat flux, static soil depth). In order to have a physically realistic model of ET in the Arctic Coastal Plain environment, these processes need to be represented within the model.

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