VIC-Glacier (VIC-GL)

Vegetation and Topography Parameterization

VIC Generation 2 Deployment Report

Volume 3

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About PCIC

The Pacific Climate Impacts Consortium is a regional climate service centre at the University of Victoria that provides practical information on the physical impacts of climate variability and change in the Pacific and Yukon Region of Canada. PCIC operates in collaboration with climate researchers and regional stakeholders on projects driven by user needs. For more information see http://pacificclimate.org.

Disclaimer

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1 Introduction

Land cover and elevation information must be provided to the VIC model in the form of several input files. Specifically, these are a vegetation parameter file, an elevation band file, and a vegetation library file. The vegetation parameter file provides a description of the distribution of land cover types (by area and elevation) within each VIC grid cell. The elevation band file summarizes the distribution of elevations in each grid cell. The vegetation library file provides physical parameters of various landcover classes.

1.1 Overview

A general overview of the information and processing steps required to produce each file is shown in Figure 1. The section references in the figure refer to the corresponding sections of this report that describes how the various data products were collected and assembled.

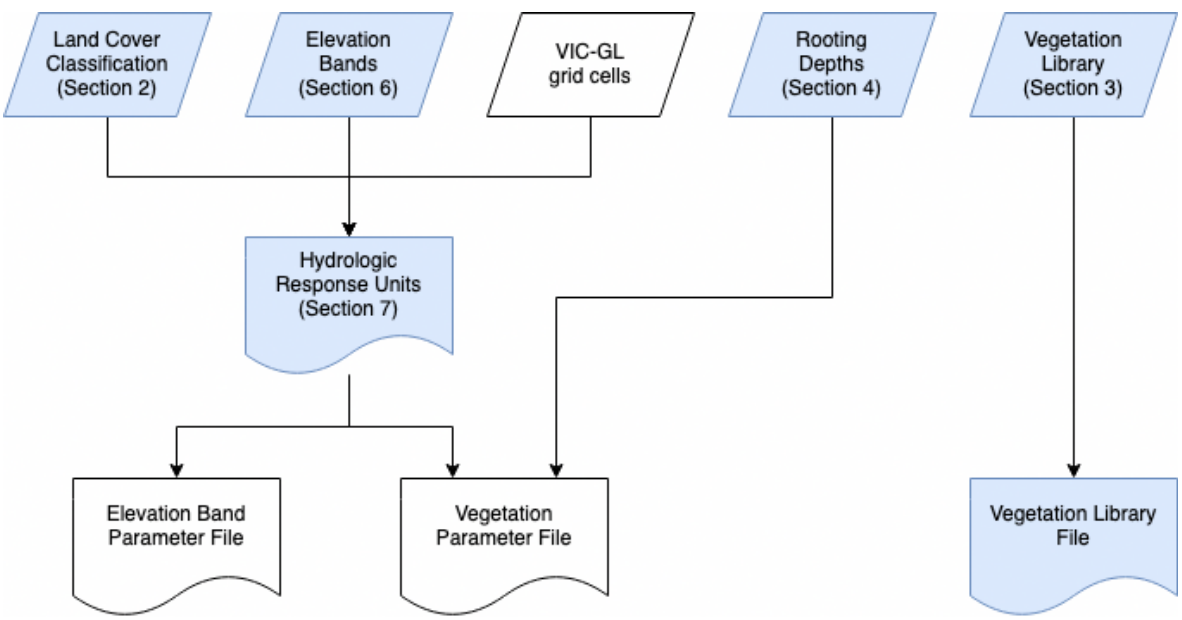


Figure 1. Overview of data requirements and processing steps to generate the vegetation and elevation band parameters and the vegetation library files. Steps colored blue are covered in this document.

For a given study area, the production of both the vegetation parameter and elevation band files requires land cover information (Section 2), rooting depth data (Section 4) and elevation distribution (Section 6). The landcover and elevation information are processed to divide each VIC computational grid into a collection of Hydrologic Response Units (HRUs; Section 7). This HRU information is then used to generate the vegetation parameter file (in conjunction with the rooting data) and the elevation band file (Figure 1). The vegetation library file is built directly from the vegetation library (Section 3). The technical steps to convert the HRU and root fraction information described herein into properly formatted vegetation and snow band parameter files is covered in a separate manual (Schnorbus 2020) and is only summarized in Section 7.

1.2 File Structure

The three input files are structured as flat text files.

1.2.1 Vegetation Parameter File Format

In the vegetation parameter file, the number of HRUs and the fraction of the grid cell covered by each HRU must be specified. The parameters are written in blocks corresponding to each grid cell. Each block begins with a cell header:

Variable Name	Units	Description
gridcell	N/A	Grid cell number (reference to soil parameter file)
Nhru	N/A	Number of HRUs in grid cell

For each grid cell the following information repeats for each HRU:

Variable Name	Units	Description
Class	N/A	Vegetation class (reference to vegetation library)
Cv	fraction	Fraction of grid cell covered by HRU
root_depth†	m	Root zone thickness (sum of depths is total of root penetration
root_fract†	fraction	Fraction of roots in current zone
band index	N/A	Elevation band index (reference to elevation band file)

† Repeats for each defined root zone (alternating between *root_depth* and *root_fract*).

An example vegetation parameter file is provided in Appendix B.

1.2.2 Elevation Band File Format

The option exists in VIC to divide each grid cell into elevation bands. Each band's median elevation is used to lapse grid cell average temperature, pressure, and precipitation to a more accurate local estimate.

This file contains information needed to define the properties of each elevation band used by the snow model. Snow elevation bands are used to improve the model's performance in areas with pronounced topography, especially mountainous regions, where the effects of elevation on snowpack accumulation and ablation might be lost in a large grid cell.

The number of snow elevation bands (*option.SNOW_BAND*) to be used with the model is defined in the global parameter file. The elevation band (or snow band) file is only read if the number of snow elevation bands is greater than 1.

It is not necessary that all grid cells in a basin have the same number of elevation bands. *SNOW_BAND* is simply the maximum number of elevation bands anywhere in the basin. For relatively flat grid cells, some of the elevation bands will have *AreaFract* values of 0. For these zero-area bands, a value of 0 may be supplied for *elevation*. The elevation band file is structured as follows:

Column	Variable Name	Units	Description
1	*gridcell*	N/A	Grid cell number (reference to soil parameter file)
2 : (*SNOW_BAND*+1)	*AreaFract*	fraction	Fraction of grid cell covered by elevation band
(*SNOW_BAND*+2) : (2**SNOW_BAND*+1)	*elevation*	m	Median elevation of band

1.2.3 Vegetation Library File Format

Vegetation parameters needed for each vegetation type used in the VIC model are provided in a column format ASCII file. Parameters are given for different vegetation types, and are referenced by the vegetation parameter file, which provides information about the number of vegetation types per grid cell, and their fractional coverage. A header may be added to the top of the file if the first column contains a '#'. Comments can also be added to the end of each line in the vegetation library file. The vegetation library file is structured as follows:

Variable Name	Units	Number of Columns	Description
class	N/A	1	Vegetation class identification
over	N/A	1	Flag to indicate presence of overstory
rarc	s/m	1	Architectural resistance of vegetation
rmin	s/m	1	Minimum stomatal resistance of vegetation
LAI	fraction	12	Monthly leaf area index
albedo	fraction	12	Monthly shortwave albedo
rough	m	12	Monthly roughness length
displacement	m	12	Monthly displacement height
wind_h	m	1	Nominal height at which wind speed is measured
RGL	W/m^2	1	Minimum incoming shortwave radiation at which there will be transpiration
rad_atten	fraction	1	Radiation attenuation factor
wind_atten	fraction	1	Wind speed attenuation factor
trunk_ratio	fraction	1	Ratio of total tree height that is trunk (no branches)
Comment	N/A	1	Comment block

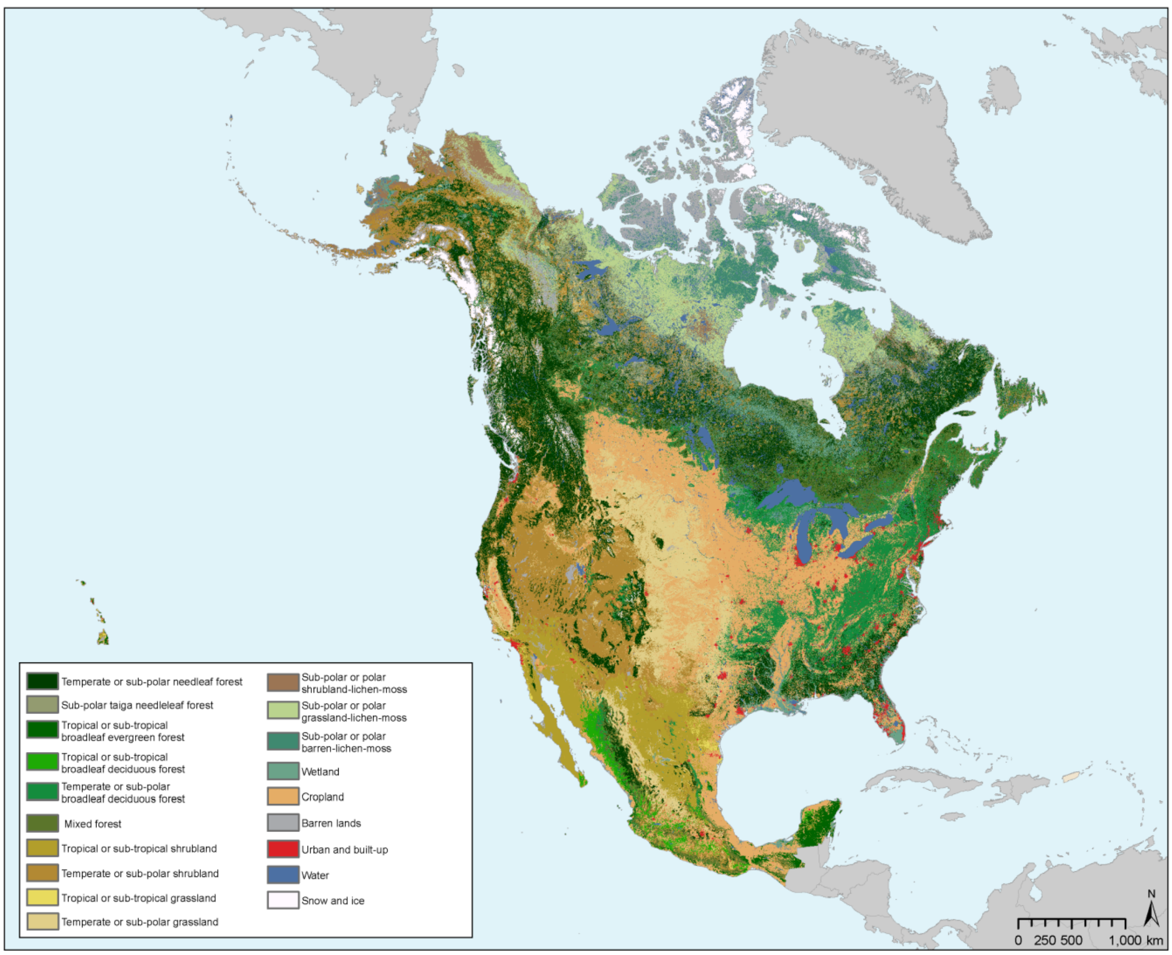
2 Land Cover Classification

Parametrization of vegetation characteristics in the VIC model is fundamentally based on discretizing the land surface into various vegetation classes. The vegetation classes are used to capture the relevant spatial variation in vegetation properties by dividing the continuum of land cover types into discrete classes, where each discrete class can be considered homogeneous with respect to a description of its properties (e.g., height, leaf area index, etc.). Ultimately, land cover classification is a tradeoff between capturing existing spatial variability while maintaining a manageable number of vegetation classes.

Given the expanded spatial domain of the hydrologic impacts program at PCIC, parameterization of the second-generation VIC application required the use of a harmonized North America-wide land cover dataset. We employed the North America Land Cover dataset (edition 2; (Natural Resources Canada/ The Canada Centre for Mapping and Earth Observation (NRCan/CCMEO) et al. 2013)) produced as part of the North America Land Change Monitoring System (NALCMS). The NALCMS land cover data set is a 250-m resolution data set that divides North America into 19 land cover classes representing c. 2005 conditions (Figure 2). NALCMS is a trilateral effort between the Canada Centre for Remote Sensing, the United States Geological Survey, and three Mexican organizations including the National Institute of Statistics and Geography (Instituto Nacional de Estadistica y Geografia), National Commission for the Knowledge and Use of the Biodiversity (Comisión Nacional Para el Conocimiento y Uso de la Biodiversidad) and the National Forestry Commission of México (Comisión Nacional Forestal). The product is based on observations acquired by the Moderate Resolution Imaging Spectroradiometer (MODIS). Mapping was performed by each country using unique data pre-processing and information extraction methodologies. These national products were subsequently used to assemble an integrated North America land cover database. The classification legend is designed in three hierarchical levels, using the Food and Agriculture Organization (FOA) Land Classification System.The collaboration is facilitated by the Commission for Environmental Cooperation (http://www.cec.org/), an international organization created by the Canada, Mexico, and United States governments under the North American Agreement on Environmental Cooperation to promote environmental collaboration between the three countries.

2.1 Sub-classification

In the original land cover classification, the *Temperate or sub-polar needleleaf forest* class occupies a rather large spatial extent within western Canada (see Figure 2). It was felt that this classification was too coarse as it did not reflect know spatial variation in the needleleaf forest class within British Columbia due to changes in elevation and differences between coastal and interior forests. Consequently, this land cover class was further subdivided using an unsupervised classification scheme based on the iterative self-organizing (ISO) clustering algorithm and maximum likelihood classification (using the Multivariate toolbox in ArcGIS). Classification was based on vegetation height (h) and leaf area index (L). The Leaf area index is defined as half the total area of green elements of the canopy per unit horizontal ground area. Leaf are index data is from the GEOV1 global time series dataset, which is a fusion of CYCLOPES v3.1 and MODIS-C5 LAI products, which are based on the SPOT/VEGETATION and MODIS sensors, respectively (Baret et al. 2013; Camacho et al. 2013). The data are available as a 10-daily time series at a spatial resolution of 1/112°. Sub-classification used the June L values for North America averaged over 2004 and 2005 (corresponding to the years of land cover classification). The L data was downloaded from the Copernicus Global Land Service at http://land.copernicus.eu/global/products/lai (last accessed September 24, 2013). Vegetation height is based on global mapping using spaceborne light detection and ranging (lidar) (Simard et al. 2011). Data is available as a global map at 1-km spatial resolution, which is based on 2005 data from the Geoscience Laser Altimeter System (GLAS) aboard ICESat (Ice, Cloud, and land Elevation Satellite). The data was downloaded from the Jet Propulsion Laboratory at http://lidarradar.jpl.nasa.gov/ (last accessed October 1, 2013).



2005 North American Land Cover at 250 m spatial resolution.

Source:
Natural Resources Canada/Canadian Centre for Remote Sensing (NRCan/CCRS), United States Geological Survey (USGS); Insituto Nacional de Estadística y Geografía (INEGI), Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (CONABIO) and Comisión Nacional Forestal (CONAFOR). 2010.

Projection: Lambert Azimuthal Equal Area
This poster was created on February 28, 2012

Figure 2. Map of original NALCMS North American land cover for 2005.

Classification was explored using both five and six sub-classes, and results are summarized in Figure 3. Leaf area index and vegetation height are strongly correlated, such that sub-classification tends to separate vegetation that is taller and denser from vegetation that is shorter and more open. For five subclasses, with the exception of the most open canopy class (lowest *L* and lowest *h*), the area of each class tends to decrease with increasing *L* and *h*; maximum area occurs at intermediate *L* and *h* when six-subclasses are used.

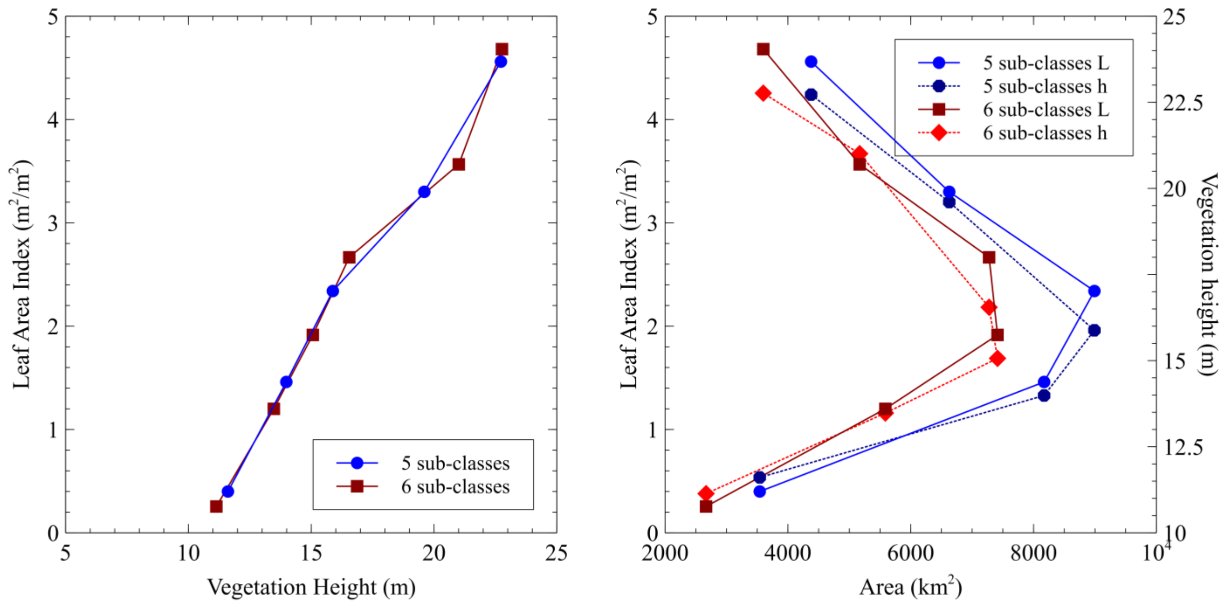


Figure 3. Summary of unsupervised ISO clustering and sub-classification of the temperate evergreen needleleaf forest class for western North America.

When clustering based on both five and six classes, the class containing the lowest *L* and *h* values is considered spurious, due to the extremely low values of *L*. Visual inspection revealed that this class tends to represent shorelines around large waterbodies and coastlines where boundaries for the respective *h*, *L* and land cover datasets are inconsistent, i.e., treed vegetation is suggested in the *h* dataset, but *L* values suggest waterbodies. This sub-class was subsequently removed from the two ISO-based sub-classifications and affected pixels were merged with the majority neighbouring land cover class from the original land cover classification. Of the two sub-classifications (now containing respectively four and five sub-classes), the smaller number of sub-classes (four) was ultimately adopted as it is thought that it provides a reasonable depiction of regional variability in temperate needleleaf tree cover. The final 22 land cover classes are summarized in Table 1.

Table 1. Land cover classes

Class	Label	Description
1	N-TeSp.1	Needleleaf Forest – temperate or sub-polar.1 – sub-alpine/sub-polar/open
2	N-TeSp.2	Needleleaf Forest – temperate or sub-polar.2 – high-elevation
3	N-TeSp.3	Needleleaf Forest – temperate or sub-polar.3 – mid-elevation
4	N-TeSp.4	Needleleaf Forest – temperate or sub-polar.4 – coastal/humid/dense
5	N-SpTa	Needleleaf Forest – sub-polar taiga
6	BE-TrSr	Broadleaf evergreen forest – tropical or sub-tropical
7	BD-TrSr	Broadleaf deciduous forest – tropical or sub-tropical
8	BD-TeSp	Broadleaf deciduous forest – temperate or sub-polar
9	MF	Mixed forest
10	S-TrSr	Shrubland – tropical or sub-tropical
11	S-TeSp	Shrubland – temperate or sub-polar
12	G-TrSr	Grassland – tropical or sub-tropical
13	G-TeSp	Grassland – temperate or sub-polar
14	SLM-SpP	Shrubland-lichen-moss – Sub-polar or polar
15	GLM-SpP	Grassland-lichen-moss – Sub-polar or polar
16	BaLM-SpP	Barren-lichen-moss – Sub-polar or polar
17	Wetland	Wetland
18	Crop	Cropland
19	Barren	Barren lands
20	Urban	Urban and built-up
21	Water	Water
22	Ice	Ice

Due to large processing requirements, the sub-classification process was only applied to an area covering the northwestern segment of North America (WNA) (Figure 4). This region represents a rectangle incorporating the proposed PCIC modelling domain, plus a rather substantive buffer region with which to accommodate potential future modelling requests.

Although an Ice class already exists in the NALCMS-based land cover inventory, the extent and location of glaciers and ice fields was updated using the more complete data of the Randolph Glacier Inventory (RGI; Pfeffer et al. 2014). The RGI is a global inventory of glacier outlines produced as a supplement to the Global Land Ice Measurements from Space initiative (GLIMS; http://www.glims.org/). Updating was based on RGI version 3.2, which was released September 2013. The RGI outlines used were from the regions Alaska, and Western Canada and USA. To complete the processing, the original land cover database had to be converted from raster to vector format. In vector format, the reclassified land cover was then merged with the RGI outlines, which were simply used as a flag to indicate the presence (TRUE) or absence (FALSE) of ice. The determination of the final land cover class was based on the set of merge rules given in Table 2.

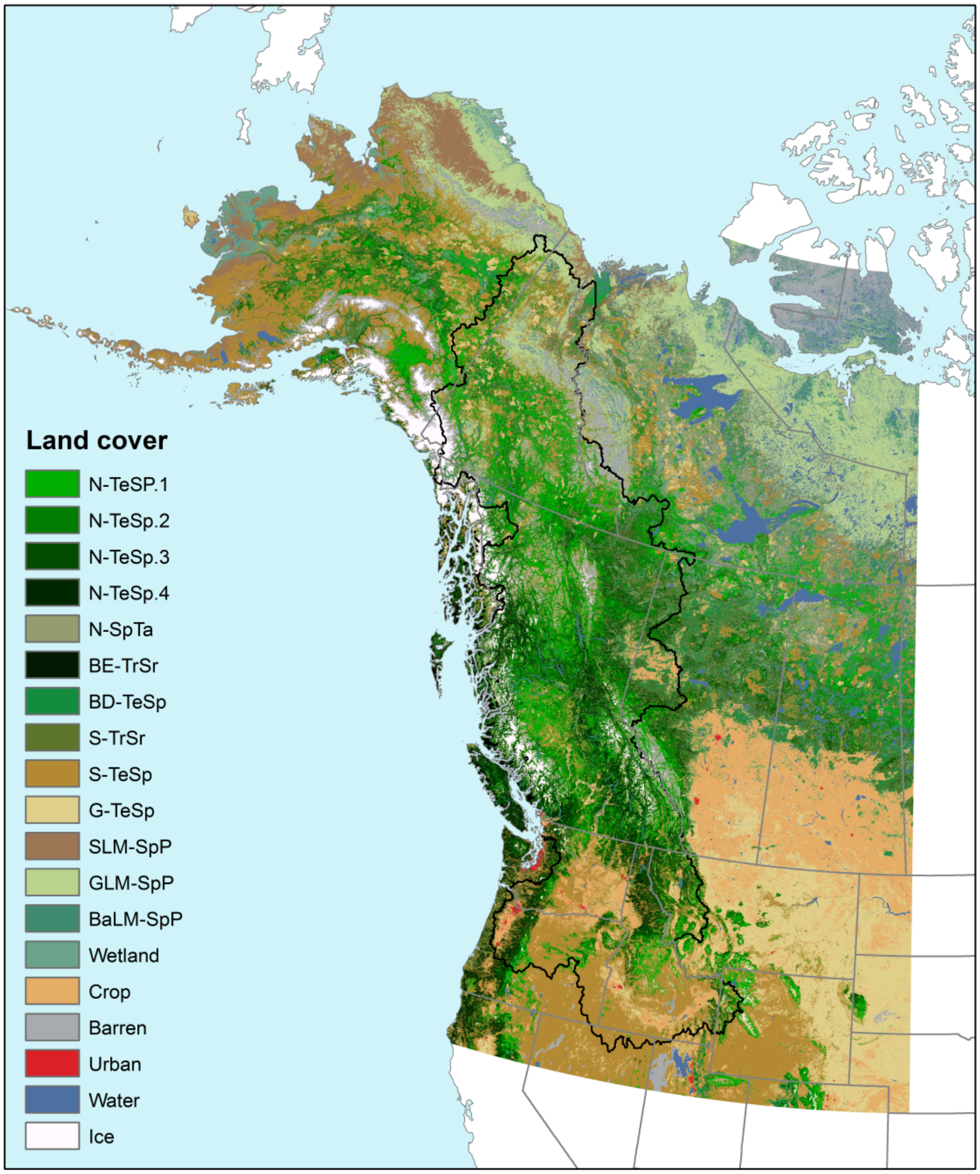


Figure 4. VIC land cover classification over the western North America (WNA) domain. Also shown is the outline for the PCIC modelling domain (black outline).

The reclassified North American land cover for the VIC application domain and the PCIC hydrologic impacts study domain is shown in Figure 4. The relative area of each land cover class within both nested domains is given in Figure 5 and Table 3. Within the WNA domain, forest classes cover only 33.7% of the area and the three largest land cover classes are S-TeSp (19.4%), G-TeSp (9.3%), and GLM-SpP (9.1%). Within the smaller PCIC domain, however, forest classes form the majority land cover (52.9%), with the forest cover consisting predominantly of needleleaf classes (43.2%). Nevertheless, S-TeSp is still the largest single class (23%) but is located almost exclusively in the Columbia River drainage. The next three largest classes by relative area in the PCIC domain are N-TeSp.2, N-TeSp.1 and N-TeSp.3 (13.9%, 12.4% and 11.3%, respectively). Note that none of the tropical or sub-tropical land cover classes (i.e., BE-TrSr, BD-TrSr, S-TrSr and G-TrSr) exists within the smaller western North America and PCIC domains.

Table 2. Update rules for merging of NALCMS and RGI land covers

NALCMS Class	RGI Flag	Final Class
Ice	TRUE	Ice
Ice	FALSE	Barren
Non-Ice	TRUE	Ice
Non-ice	FALSE	Original Class

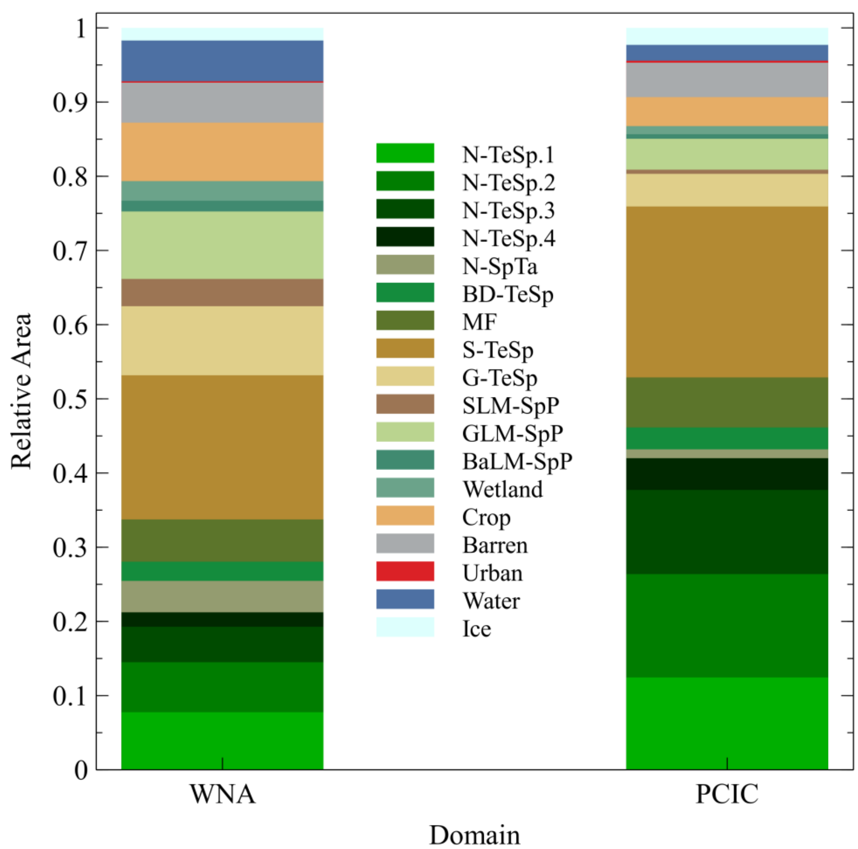


Figure 5. Relative area of VIC land cover classes in the western North America (WNA) and PCIC domains

Table 3. Area of land cover classes within the western North America and PCIC domains

Class	Label	Relative Area	
		Western NA	PCIC
1	N-TeSp.1	0.078	0.124
2	N-TeSp.2	0.067	0.139
3	N-TeSp.3	0.048	0.113
4	N-TeSp.4	0.019	0.043
5	N-SpTa	0.042	0.012
6	BE-TrSr	0.0	0.0
7	BD-TrSr	0.0	0.0
8	BD-TeSp	0.026	0.029
9	MF	0.057	0.067
10	S-TrSr	0.0	0.0
11	S-TeSp	0.194	0.230
12	G-TrSr	0.0	0.0
13	G-TeSp	0.093	0.044
14	SLM-SpP	0.037	0.006
15	GLM-SpP	0.091	0.042
16	BaLM-SpP	0.014	0.006
17	Wetland	0.026	0.011
18	Crop	0.079	0.039
19	Barren	0.054	0.046
20	Urban	0.002	0.003
21	Water	0.055	0.021
22	Ice	0.017	0.023

3 Vegetation Library

Most vegetation parameters are stored as class-specific values in a look-up table, or vegetation library file. A description of the parameters stored in the vegetation library file is provided as Table 4. The specifics of the derivation and estimation of appropriate values is discussed for each parameter in the following sub-sections. An example vegetation library file is given in Appendix B.

3.1 Overstory

The *over* parameter is simply a binary flag, where 1 indicates TRUE (i.e., overstory present) and 0 indicates FALSE (i.e., no overstory present). The overstory flag essentially distinguishes between tree and non-tree vegetation. This distinction is inferred from the land cover classes themselves, where all forest vegetation classes plus the urban class are assumed to have an overstory present. Overstory values by vegetation class are summarized in Table 5.

Table 4. Vegetation parameters in the Vegetation Library

Parameter	Description	References
over	Overstory flag	Inferred from NALCMS land cover data
r_{arc}	Architectural resistance (s/m)	Ducoudré et al. (1993)
r_{min}	Minimum stomatal resistance (s/m)	Lafleur (1988); Munro (1989); Schulze et al. (1994)
L	Monthly one-sided leaf area index (m^2/m^2)	Baret et al. (2013); Camacho et al. (2013)
α	Monthly albedo (-)	Dickinson (1983); Sellers (1985); Dorman and Sellers (1989)
z_o	Monthly roughness length (m)	Amiro (1990); Choudhury and Monteith (1988)
d	Monthly displacement height (m)	Amiro (1990); Choudhury and Monteith (1988)
z_{ref}	Wind measurement reference height (m)	Simard et al. (2011)
R_{50}	Incoming shortwave radiation at which stomatal resistance is twice its minimum value (W/m^2)	Dickinson et al. (1991)
δ	Canopy wind extinction coefficient (-)	Kondo (1971)
k	Solar radiation canopy extinction coefficient (-)	Dickinson (1983); Sellers (1985); Dorman and Sellers (1989)
tr	Ratio of total tree height that is trunk (i.e. no branches) (-)	Toney and Reeves (2009)

Table 5. Vegetation library values for non-seasonal parameters.

Class	Parameters								
	over	r_{arc}	r_{min}	z_{ref}	R_{50}	$k^{‡}$	δ	*tr*	*h*
1	1	50	182	30	30	0.87	1.97	0.30	16
2	1	50	182	30	30	0.82	2.30	0.30	18
3	1	50	182	30	30	0.79	2.62	0.30	23
4	1	50	182	40	30	0.77	2.89	0.30	29
5	1	50	182	20	30	0.89	1.68	0.30	11
6	1	25	172	40	30	0.69	3.36	0.30	26
7	1	40	172	40	30	0.71	1.35	0.60	16
8	1	40	169	30	30	0.75	1.35	0.60	16
9	1	45	217	30	30	0.84	2.08	0.45	15
10	0	2.5	172	10	30	0.77	0.00	0.00	2
11	0	2.5	169	10	30	0.77	0.00	0.00	2
12	0	2	175	10	30	0.76	0.00	0.00	1
13	0	2	130	10	30	0.76	0.00	0.00	1
14	0	2.5	169	10	30	0.79	0.00	0.00	1
15	0	10	161	10	30	0.78	0.00	0.00	0.25
16	0	10	161	10	30	0.84	0.00	0.00	0.1
17	0	3	100	10	30	0.78	0.00	0.00	2
18	0	2	93	10	30	0.66	0.00	0.00	1*
19	0	9999	9999	10	9999	0.00	0.00	0.00	0.1
20	1	31	217	20	30	0.83	2.04	0.45	11
21	0	9999	9999	10	9999	0.00	0.00	0.00	0.05
22	0	9999	9999	10	9999	0.00	0.00	0.00	0.05

‡ Based on a latitude of 55°N

* Crop value represents seasonal maximum

3.2 Architectural Resistance

Architectural resistance, r_{arc}, is described as the resistance that is due to the variation of the gradient of specific humidity between the leaves and the overlying air in the canopy layer (Liang et al. 1994). Representative values of r_{arc} are provided by Ducoudré et al. (1993) for tundra, grassland, deciduous forest, evergreen forest and rainforest. These values have been applied directly to most of the current 22 land cover classes. Exceptions are the MF class, which is an average of deciduous and evergreen forest, and the Urban class, which is an average of evergreen forest, deciduous forest, and grassland. Arbitrarily large values of 9999 are used for the Barren, Water, and Ice land cover classes. Final library values are given in Table 5.

3.3 Minimum Stomatal Resistance

The minimum stomatal resistance, r_{min}, is the resistance to plant vapor transport that occurs under ideal conditions, i.e. during periods of high solar radiation, optimum air temperature, and low (or non-existent) vapor and soil moisture deficits (Baird and Wilby 1999). Although the VIC model requires stomatal resistance, literature values describing plant vapor transport typically report conductance values (which are the inverse of resistance). Hence, minimum resistance corresponds to maximum conductance. For the majority of land cover classes, conductance values were taken from Schulze et al. (1994). The resistance for the Wetland class is based on a composite of values for wetland and marsh vegetation obtained from Lafleur (1988) and Munro (1989). The resistance value for the Urban class is the average of values for needleleaf forest, broadleaf deciduous forest, and grassland. Resistances for the Barren, Water and Ice classes are set to an arbitrarily high value of 9999. Minimum stomatal resistance values are summarized in Table 5.

3.4 Wind Height

The wind height parameter z_{ref} is the height above the ground at which wind observations are considered to be recorded. Typically wind observations are taken at a height of 2 m in clearings. However, the VIC model assumes wind observations are made above the vegetation cover in each grid cell and that wind speeds through and below the canopy can be found using exponential and logarithmic wind profiles. For short vegetation types (grasses, shrubs, etc.) the wind measurement height can be set to ~2 m above the top of the vegetation. For tall vegetation types (trees), especially those defined with an overstory, the wind measurement height should be set much higher than the vegetation. This is physically justified because a forest canopy impacts atmospheric stability to a much higher elevation, than shorter vegetation. If the model is required to run with an overstory defined, and the wind height set to just above the vegetation (for example the tree height + 2m) large negative evaporations and sublimations may be found during the winter months, as the snow interception algorithm is forced to use unrealistically strong wind speeds. Wind height is therefore set to be approximately 10 m higher than the vegetation height, rounded to the nearest 10-m value. For example, if the vegetation height is 16m, then the wind height is given as 16 + 10 rounded to the nearest 10, which is 30m. Library wind height values are given in Table 5.

3.5 R50

The R_{50} parameter is used to describe the dependence of stomatal resistance on solar radiation. R_{50} is defined as the value of photosynthetically active radiation (PAR) at which stomatal resistance is $2r_{min}$. Due to limited available information, we set this value the same for all land cover classes, using the mid-point of 10-50 W/m^2 range (30 W/m^2) suggested by Dickinson et al. (1991). For the Barren, Water, and Ice classes, R_{50} is set to an arbitrarily high value of 9999 W/m^2. The final R_{50} library values are given in Table 5.

3.6 Solar Radiation Attenuation Factor

Direct beam solar radiation incident on a vegetation canopy will be attenuated according to an exponential extinction as (Campbell and Norman 1998)

$$I_L = I_0 \exp(-kL) \quad (1)$$

where I_0 is incident radiation above the canopy (W/m^2), I_L is the radiation below a canopy of leaf area index *L* and *k* is the solar radiation attenuation factor, which is calculated from

$$k = [G(\mu)/\mu](1-\omega)^{1/2} \quad (2)$$

where $G(\mu)$ is the relative projected area of leaf elements in the direction $\cos^{-1}\mu$, μ is the solar zenith angle, and ω is the leaf scattering coefficient, which is equal to $\rho+\tau$, where ρ is the leaf-element reflectance and τ is the leaf-element transmittance. Separate optical parameters ρ and τ are provided for the visible (vis) and near-infrared (nir) bands, and values for each land cover class are given in Table 6 (adapted from Dorman and Sellers 1989). $G(\mu)$ can be estimated as a function of χ_L using (Sellers 1985)

$$G(\mu) = \phi_1 + \phi_2\mu \quad (3)$$

where $\phi_1 = 0.5 - 0.633\chi_L - 0.33\chi_L^2$ and $\phi_2 = 0.877(1 - 2\phi_1)$. The χ_L function describes the departure of leaf angles from the spherical distribution, where χ_L = 0 for spherically arranges leaves, +1 for horizontal leaves and -1 for vertical leaves. The value of *k* is strongly dependent on the solar zenith angle and hence will vary depending upon the time of day, day of year, and latitude (Figure 6a). However, *k* is not as sensitive to either χ_L (Figure 6a) or the scattering coefficient, ω (not shown). The value of χ_L for each land cover class is also given in Table 6.

Despite the dependency on zenith angle and the fact that many of the VIC land cover classes span a large latitudinal range (c.f. Figure 4), the VIC model only uses a single value of *k* for the entire year for each class. This presents some challenges with respect to selecting a suitable value for *k* for a given land cover class. The approach adopted has been to estimate an effective annual solar radiation attenuation factor, k_e. Here k_e is defined as the value which satisfies the following relationship

$$\sum_{m=1}^{12}\sum_{t=1}^{24} I_0(m,t)\exp[-k_e L(m)] = \sum_{m=1}^{12}\sum_{t=1}^{24} I_0(m,t)\exp[-k(\mu_t)L(m)] \quad (4)$$

where k_e is the constant solar attenuation coefficient that produces the same annual below canopy radiation as that produced using *k* that varies with time (i.e. solar zenith angle) and monthly *L*. Note that k_e is not solved by integrating over the entire year, rather equation (4) assumes that seasonal variation can be captured by integrating over a single representative day for each month, *m* (as per albedo, see §3.10), with each day integrated with an hourly time interval, *t*. Hence k_e is an insolation-weighted and *L*-weighted annual average value of $k(\mu)$. Equation (4) must be solved iteratively for specific latitudes.

Note that in equation (4) I_0 is represented using extraterrestrial solar radiation, which is calculated using solar geometry (e.g. Campbell and Norman 1998).

For the Barren, Water and Ice land cover classes, *k* is set to zero. The final effective *k* values are given in Table 5. The impact of using an effective annual *k* value is shown in Figure 7, which compares hourly below-canopy solar radiation (I_L) calculated using a dynamic *k* value (i.e., estimated hourly as a function of solar zenith angle and monthly *L*) with that estimated using k_e. In all months, using k_e tends to overestimate I_L during the early and late hours of the day. Using an effective solar attenuation factor also modifies the diurnal amplitude of I_L, where it is lower in June, but much higher in December than values calculated using dynamic *k* values. The value of k_e is also latitude-specific, where k_e increases with increasing latitude (Figure 8), and values corresponding to 55°N latitude have been chosen for final VIC parameterization. This latitude roughly corresponds to the central northing of the PCIC modelling domain (c.f. Figure 4).

Table 6. Optical and morphological properties for each land cover class.

Class	ρ_{vis}	ρ_{nir}	τ_{vis}	τ_{nir}	χ_L
1	0.07	0.35	0.05	0.10	0.01
2	0.07	0.35	0.05	0.10	0.01
3	0.07	0.35	0.05	0.10	0.01
4	0.07	0.35	0.05	0.10	0.01
5	0.07	0.35	0.05	0.10	0.01
6	0.10	0.45	0.05	0.25	0.10
7	0.10	0.45	0.05	0.25	0.25
8	0.10	0.45	0.05	0.25	0.25
9	0.07	0.40	0.05	0.15	0.13
10	0.10	0.45	0.05	0.25	0.10
11	0.10	0.45	0.05	0.25	0.10
12	0.11	0.58	0.07	0.25	-0.30
13	0.11	0.58	0.07	0.25	-0.30
14	0.10	0.45	0.05	0.25	0.10
15	0.11	0.58	0.07	0.25	-0.30
16	0.11	0.58	0.07	0.25	-0.30
17	0.10	0.45	0.05	0.25	0.10
18	0.11	0.58	0.07	0.25	-0.30
19	0.001	0.001	0.001	0.001	0.01
20	0.07	0.40	0.05	0.15	0.13
21	0.02	0.00	0.9	0.40	0.25
22	0.80	0.70	0.03	0.01	0.25

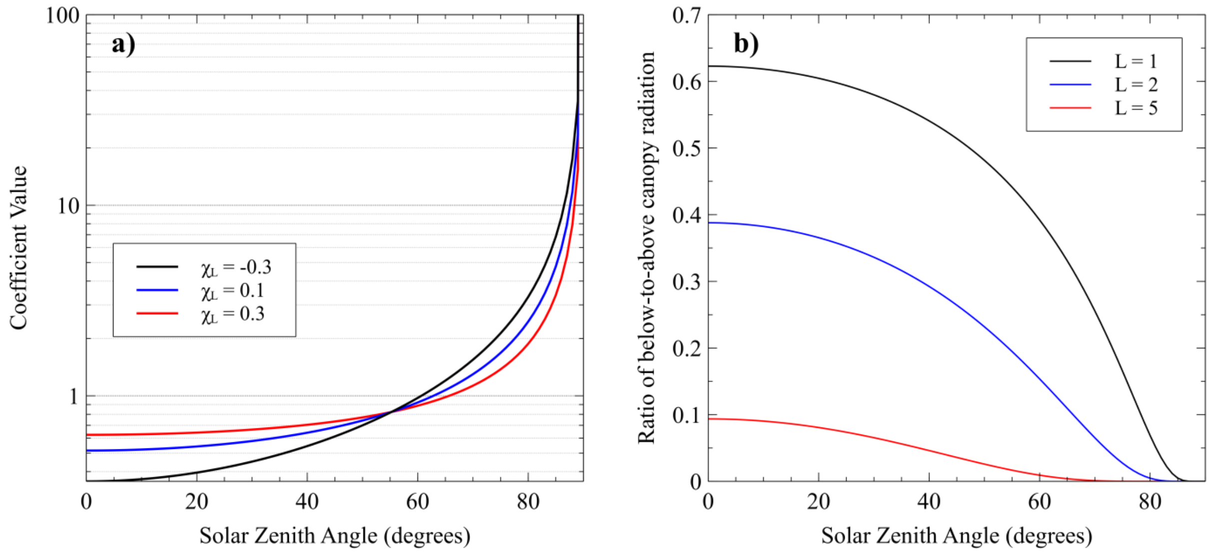


Figure 6. Variation of solar radiation through a vegetation canopy showing a) the value of the extinction coefficient, *k*, as a function of solar zenith angle and leaf angle distribution, and b) the ratio of below- to above-canopy solar radiation for various *L* values. Calculations are based on the optical parameters for needleleaf evergreen trees (ρ_{vis}=0.07, τ_{vis}=0.05 and χ_L=0.01).

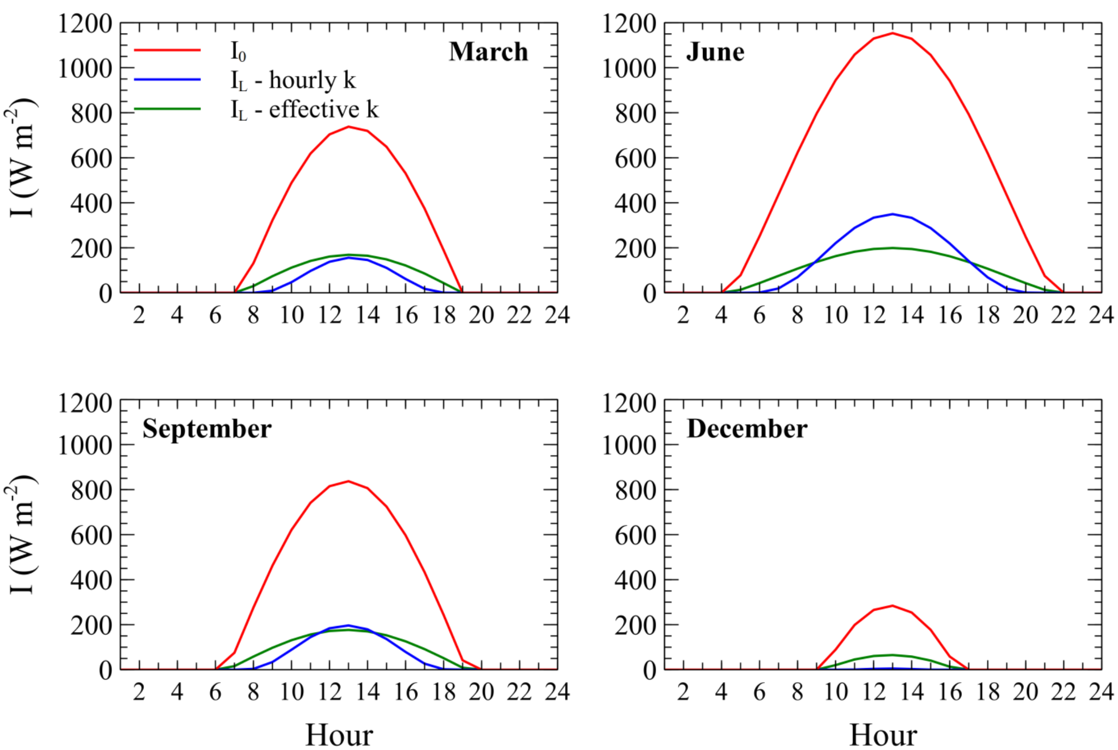


Figure 7. Comparison of above- and below-canopy hourly solar radiation, comparing below-canopy radiation calculated using hourly *k* and effective annual *k* (k_e) for representative days in March, June, September, and December. Calculations are for vegetation class N-TeSp.2 (*L* is 1.8, 1.8, 2.1 and 1.9 for March, June, September, and December, respectively). Above-canopy solar radiation (I_0) is represented using extraterrestrial solar radiation.

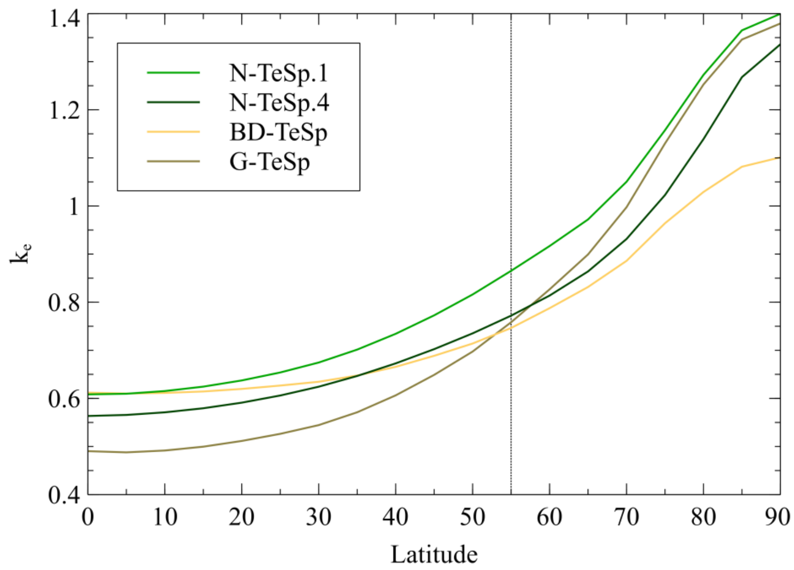


Figure 8. Variation of annual effective solar attenuation factor with latitude for representative land cover classes. The vertical grey line shows the target latitude of 55°N

3.7 Wind Attenuation Factor

To model wind within overstory vegetation, VIC divides the vertical distribution of wind speed into three distinct vertical profiles: logarithmic above the canopy, exponential within the canopy and logarithmic in the trunk space below the canopy. In the canopy layer the wind decreases exponentially with depth, where the wind speed, *u*, at height *z* is given by (Wigmosta et al. 1994)

$$u(z) = u(h) \cdot exp\left[\delta\left(\frac{z}{h} - 1\right)\right] \quad (5)$$

where *u*(*h*) is the wind speed at the top of the canopy and δ is the wind attenuation (or extinction) coefficient. The wind attenuation coefficient, δ, is calculated as (Kondo 1971)

$$\delta = 1 \Big/ \left\{\left(1 - \frac{d}{h}\right) \ln\left[\left(1 - \frac{d}{h}\right) \Big/ \left(\frac{z_0}{h}\right)\right]\right\}. \quad (6)$$

Figure 9a shows the sensitivity of δ on the displacement height, *d*, and the roughness length, z_0 (§3.11 describes the estimation of *d* and z_o). Dependence of δ on *d* and z_0 also implies dependence on *L* and C_D (see equations (12) and (13); Figure 9b). Despite its dependence on *L*, which varies seasonally, VIC uses only a single wind attenuation value for the year. Hence, calculation of δ using (6) is based on class-specific values of d/h and z_0/h estimated using an annual average *L* value (i.e., an average of the twelve monthly values). The wind attenuation factor is only calculated for treed vegetation (i.e., *over*=1); the value of δ is set to zero for non-treed vegetation. The effect of δ on the wind profile is shown in Figure 10a. Library values for the wind attenuation factor are given in Table 5.

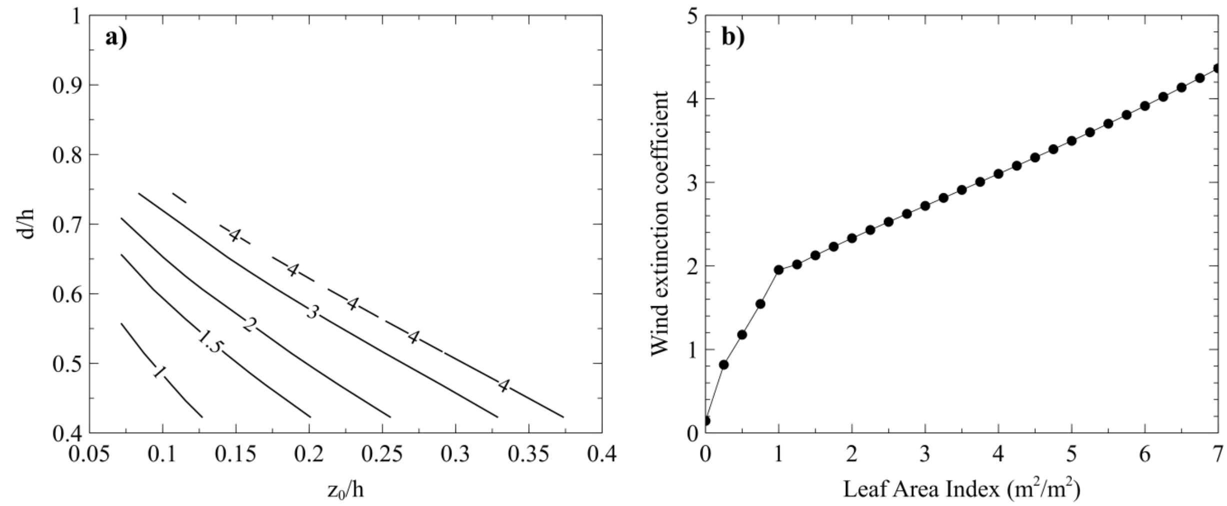


Figure 9. Wind attenuation factor as a function of a) roughness length and displacement height, and b) leaf area index using C_D = 0.2, z_0' = 0.01m and *h* = 20m.

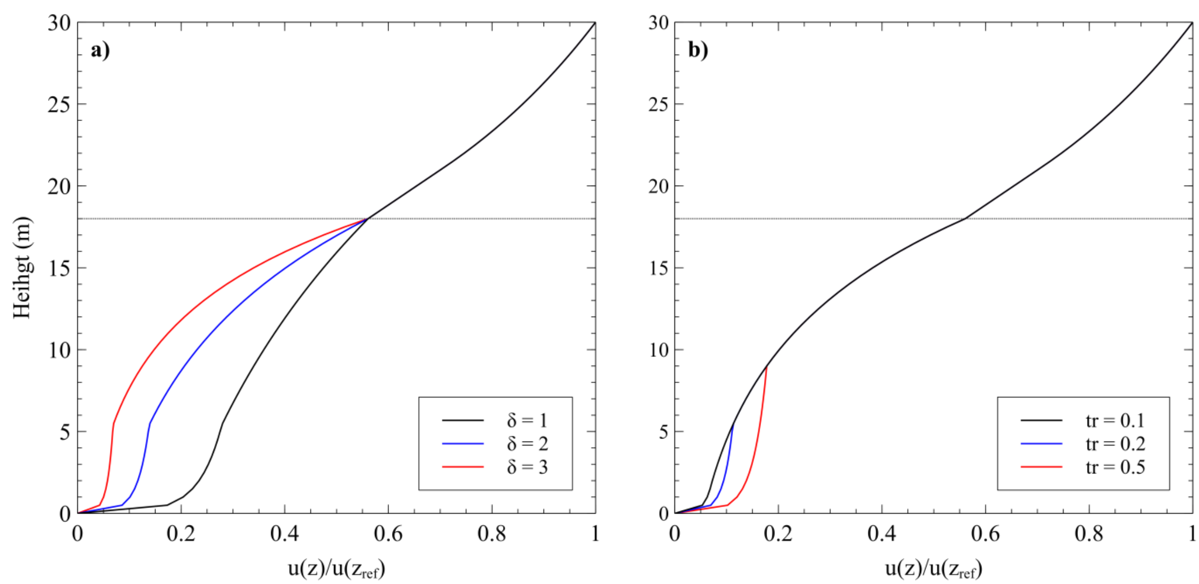


Figure 10. Wind profile through a tree canopy (land cover class N-TeSp.2) as a function of a) wind attenuation factor *δ* and b) trunk ratio *tr*. Original vegetation parameters are *h*=18 m, z_{ref}=30 m, *δ*=2.3 and *tr*=0.3. The dashed horizontal line indicates the vegetation height.

3.8 Trunk Ratio

Values for the trunk ratio, *tr*, the ratio of trunk space (portion of tree bole without branches) to total vegetation height, *h*, were adapted from data provided by Toney and Reeves (2009). The *tr* parameter determines the height of the below-canopy logarithmic wind profile for forest land cover classes. Data were provided in the form of the uncompressed crow ratio, *ucr*, where *tr* = 1 – *ucr*, for several tree species throughout western North America. For our purposes, we separated the data into conifer and deciduous species, further isolating data for species that grow within the PCIC study domain (conifer: grand fir, subalpine fir, Rocky Mountain juniper, western larch, Engelmann spruce, whitebark pine, lodgepole pine, western white pine, ponderosa pine, Douglas fir, western red cedar, western hemlock, and mountain hemlock; deciduous: paper birch, quaking aspen, and black cottonwood). Composite values were estimated by taking the weighted (by the number of trees sampled) average of 1- mean *ucr* provided for each species. The final *tr* values for conifer and deciduous species are 0.33 and 0.64, respectively. A *tr* value is only calculated for treed vegetation (i.e. *over* = 1); *tr* for non-treed vegetation is set to zero. The influence of the *tr* parameter on the vertical wind speed profile below the forest canopy is shown in Figure 10b. Trunk ratio values are provided in Table 5.

3.9 Monthly Leaf Area Index

Monthly leaf area index values for each land cover class were estimated from the GEOV1 Leaf Area Index version 1 product (see §2.1). Monthly values of the 10-daily global GEOV1 data product were created by averaging gridded values over a 30-day window centred on a given month, and then averaged again over the years 2004 and 2005. This monthly gridded data set was then used to calculate zonal statistics for each land cover class over the western North America domain using the zonal statistics toolset in the ArcGIS software package. The class-specific *L* value was based on the median GEOV1 value for each class. Due to the effect of snow cover on sensor performance, monthly *L* values are only available for the months of April through October. These raw GEOV1-based *L* values were extrapolated to the remaining months and temporally smoothed by fitting the GEOV1-based *L* values to a fourth-order polynomial. A final adjustment included some manual tuning of needleleaf values to ensure that the seasonal amplitude agreed with the results of Dorman and Sellers (1989). Final monthly *L* values for the vegetation library are provided in Table 7. Representative *L* values are also shown in Figure 11.

3.10 Monthly Albedo

Monthly albedo was estimated using two-stream radiation model described by Dickinson (1983) and Sellers (1985). In this approach, the canopy albedo is sum of the direct and diffuse components of albedo. For direct beam radiation

$$\left.\begin{aligned} I\uparrow &= \frac{h_1 \exp(-kL)}{\sigma} + h_2 \exp(-hL) + h_3 \exp(hL) \\ I\downarrow &= \frac{h_4 \exp(-kL)}{\sigma} + h_5 \exp(-hL) + h_6 \exp(hL) \end{aligned}\right\} \qquad (7)$$

Table 7. Library values of the monthly leaf area index parameter.

Class	Monthly Leaf Area Index, *L* (m^2/m^2)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	1.0	1.0	1.0	1.1	1.3	1.4	1.6	1.3	1.2	1.1	1.0	1.0
2	1.8	1.8	1.8	1.9	2.0	2.1	2.4	2.0	1.9	1.8	1.8	1.8
3	2.5	2.5	2.5	2.8	3.0	3.3	3.3	3.0	2.8	2.5	2.5	2.5
4	3.2	3.2	3.2	3.5	3.7	4.2	4.1	3.5	3.3	3.2	3.2	3.2
5	0.7	0.7	0.7	0.8	0.9	0.9	1.0	1.0	1.0	0.9	0.8	0.7
6	4.3	4.3	4.3	4.6	5.0	5.4	5.4	5.0	4.6	4.3	4.3	4.3
7	4.3	4.3	4.3	4.6	5.0	5.4	5.4	5.0	4.6	4.3	4.3	4.3
8	0.2	0.2	0.2	0.2	0.5	1.6	2.0	1.5	0.4	0.2	0.2	0.2
9	0.9	0.9	0.9	1.1	1.4	2.5	2.8	2.0	1.5	1.0	0.9	0.9
10	0.3	0.3	0.3	0.5	0.9	1.1	1.2	1.0	0.7	0.3	0.3	0.3
11	0.3	0.3	0.3	0.5	0.9	1.1	1.2	1.0	0.7	0.3	0.3	0.3
12	0.3	0.3	0.3	0.5	0.6	0.9	0.8	0.6	0.3	0.3	0.3	0.3
13	0.3	0.3	0.3	0.5	0.6	0.9	0.8	0.6	0.3	0.3	0.3	0.3
14	0.5	0.5	0.5	0.7	0.9	1.2	1.3	1.3	1.1	0.8	0.5	0.5
15	0.4	0.4	0.4	0.5	0.5	0.7	0.9	0.8	0.6	0.5	0.4	0.4
16	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
17	0.7	0.7	0.7	0.8	1.3	1.6	1.7	1.5	1.2	1.0	0.7	0.7
18	0.0	0.1	0.2	0.2	0.5	1.6	2.0	1.5	0.4	0.2	0.1	0.0
19	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
20	0.8	0.8	0.8	1.5	1.9	2.0	2.0	1.8	1.4	1.1	0.8	0.8
21	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
22	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

and for diffuse radiation

$$\left.\begin{aligned} I\uparrow &= h_7\exp(-hL) + h_8\exp(hL) \\ I\downarrow &= h_9\exp(-hL) + h_{10}\exp(hL) \end{aligned}\right\}, \tag{8}$$

where $I\downarrow$ and $I\uparrow$ are the upward and downward diffuse radiative fluxes normalized by the incident flux, *L* is cumulative leaf area index (0 at the top of the canopy, increasing downward), *k* is the optical depth of direct beam per unit leaf area (also known as the radiation attenuation factor; see §3.6), and the constants σ and h_1 through h_{10} are functions μ, and ω. Details on the calculation of the constants is given in the Appendix of Sellers (1985).

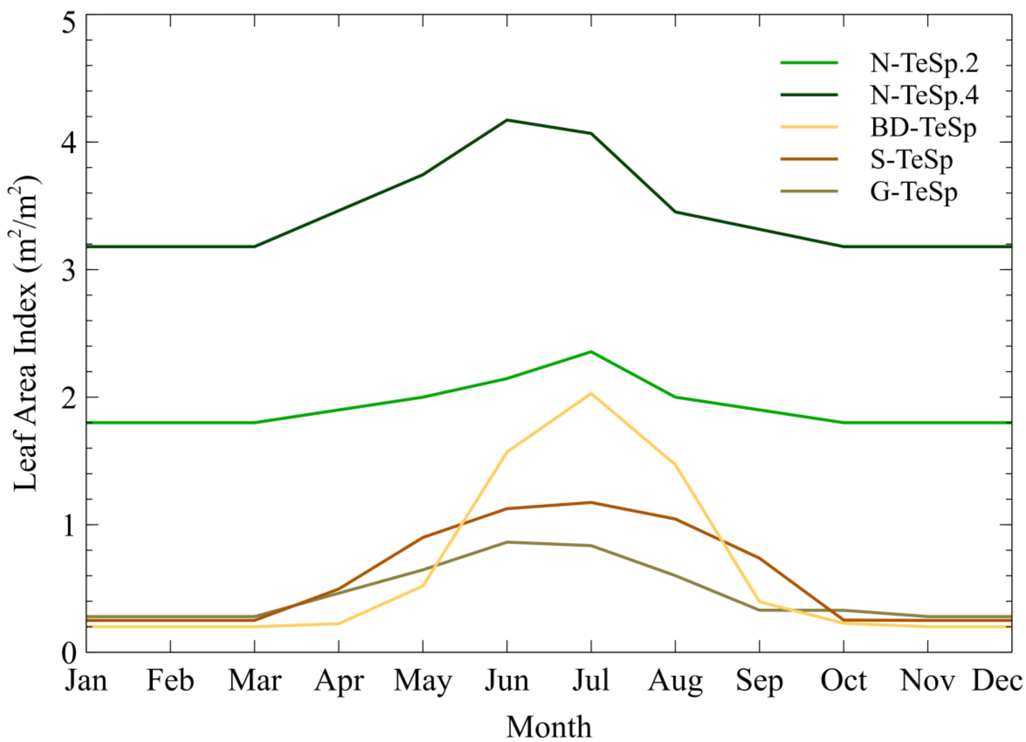


Figure 11. Monthly leaf area index values for representative land cover classes.

Canopy albedo for each band is then simply given as the upward radiative flux at the top of the canopy

$$\alpha_{band}(\mu) = I \uparrow (L = 0) = \frac{h_1}{\sigma} + h_2 + h_3 + h_7 + h_8. \quad (9)$$

The canopy albedo is calculated for each band separately using (9) from which the broadband albedo is estimated as (Liang 2001)

$$\alpha(\mu) = 0.6\alpha_{vis}(\mu) + 0.4\alpha_{nir}(\mu). \quad (10)$$

Monthly mean albedo values are estimated using representative days for each month (Table 8; Sabziparvar 2008). Based on these representative days, monthly-average albedo is set equal to the insolation-weighted daily average albedo value

$$\alpha_m = \frac{\sum_{t=1}^{24} I_0(\mu_t)\alpha(\mu_t)}{\sum_{t=1}^{24} I_0(\mu_t)}. \quad (11)$$

Solar zenith angles for the calculation of monthly albedo use a latitude of 55°N. Final library albedo values are given in Table 9.

Table 8. Representative days in each month for monthly mean calculations.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Day	17	15	16	15	15	11	17	16	16	16	15	11

Table 9. Library values of the monthly albedo parameter.

Class	Monthly Albedo, α (m^2/m^2)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	0.11	0.11	0.10	0.10	0.09	0.09	0.09	0.09	0.10	0.10	0.11	0.11
2	0.10	0.09	0.09	0.08	0.08	0.08	0.08	0.08	0.09	0.09	0.09	0.10
3	0.09	0.09	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.09	0.09	0.10
4	0.09	0.09	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.09	0.09	0.10
5	0.12	0.12	0.12	0.11	0.11	0.11	0.10	0.10	0.11	0.11	0.12	0.12
6	0.16	0.15	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.15	0.16	0.16
7	0.16	0.15	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.15	0.16	0.16
8	0.19	0.19	0.19	0.17	0.15	0.14	0.14	0.14	0.16	0.17	0.19	0.19
9	0.13	0.13	0.13	0.12	0.11	0.10	0.10	0.10	0.11	0.12	0.13	0.13
10	0.19	0.19	0.18	0.17	0.15	0.15	0.15	0.15	0.16	0.19	0.19	0.19
11	0.19	0.19	0.18	0.17	0.15	0.15	0.15	0.15	0.16	0.19	0.19	0.19
12	0.21	0.20	0.20	0.19	0.18	0.18	0.18	0.19	0.20	0.20	0.21	0.21
13	0.21	0.20	0.20	0.19	0.18	0.18	0.18	0.19	0.20	0.20	0.21	0.21
14	0.18	0.17	0.17	0.16	0.15	0.15	0.14	0.15	0.15	0.16	0.18	0.18
15	0.21	0.20	0.20	0.19	0.19	0.18	0.18	0.18	0.19	0.20	0.20	0.21
16	0.21	0.20	0.20	0.19	0.19	0.19	0.19	0.19	0.19	0.20	0.20	0.21
17	0.17	0.17	0.16	0.16	0.14	0.14	0.14	0.14	0.15	0.16	0.17	0.17
18	0.21	0.21	0.20	0.20	0.19	0.18	0.18	0.18	0.19	0.20	0.21	0.21
19	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21
20	0.13	0.13	0.13	0.11	0.10	0.10	0.10	0.10	0.11	0.12	0.13	0.14
21	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
22	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65

3.11 Monthly Roughness and Displacement

Both the zero plane displacement, *d*, and the roughness length, z_0, for each vegetation class are taken to vary as a function of both vegetation height, *h*, and leaf area index, *L* (e.g. Campbell and Norman 1998). Displacement and roughness are calculated as (Choudhury and Monteith 1988)

$$d = 1.1h\ln(1 + X^{\frac{1}{4}}) \qquad (12)$$

and

$$z_o = \begin{cases} z_o' + 0.3hX^{\frac{1}{2}} & 0 \le X \le 0.2 \\ 0.3h(1 - d/h) & 0.2 < X \le 1.5 \end{cases} \tag{13}$$

where z_o' is the soil roughness (0.01m), $X = C_D L$ and C_D is the mean drag coefficient. Both d and z_o were calculated monthly using monthly values of L (see §3.9). The mean drag coefficient is set to a value of 0.2 and is assumed to be uniform through the canopy (Amiro 1990). The sensitivity of d and z_o as a function of L and C_D is shown in Figure 12. Values of d and z_o for each land cover class are given in Table 10 and Table 11, respectively.

Vegetation height, h, although not a parameter of the VIC model, is required to estimate d and z_o. For the majority of land cover classes vegetation height was estimated from the global dataset of Simard et al. (2011) (see §2.1) by calculating the zonal median for each land cover class over the western North America domain. For the Barren, Water, Ice and Wetland classes, heights are arbitrarily set to 0.1m, 0.05m, 0.05m and 2.0m, respectively.

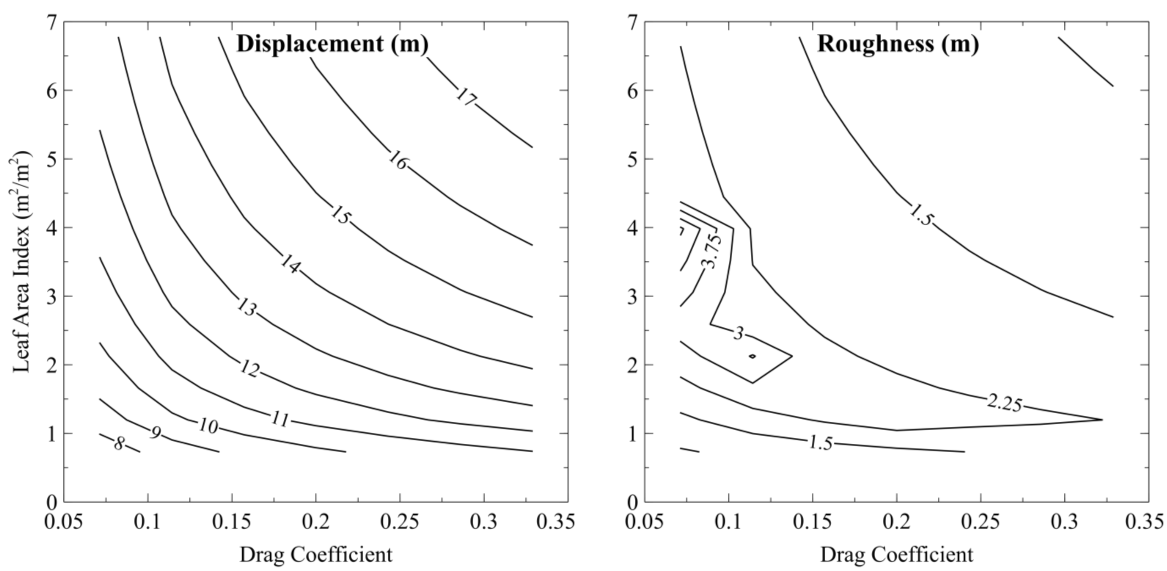


Figure 12. Contour plots of a) zero plane displacement, and b) roughness length as a function of drag coefficient and leaf area index for a vegetation height of 20 m.

Vegetation height is assumed constant throughout the year for all vegetation classes except crop vegetation. The vegetation height for the Crop class was assumed to vary seasonally with L, from a maximum in July (value of 1m) to 0m in December and January. Final library values for vegetation heights are provided in Table 5.

Table 10. Library values of the monthly zero plane displacement height parameter.

Class	Monthly Zero Plane Displacement Height, *d* (m)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	9.01	9.01	9.01	9.18	9.42	9.63	9.82	9.43	9.29	9.13	9.01	9.01
2	11.36	11.36	11.36	11.47	11.59	11.74	11.95	11.59	11.47	11.36	11.36	11.36
3	15.44	15.44	15.44	15.72	15.97	16.24	16.23	15.97	15.72	15.44	15.44	15.44
4	20.36	20.36	20.36	20.68	20.98	21.40	21.30	20.67	20.52	20.36	20.36	20.36
5	5.81	5.81	5.81	5.91	6.00	6.12	6.20	6.19	6.15	6.05	5.88	5.81
6	19.31	19.31	19.31	19.56	19.81	20.09	20.09	19.81	19.57	19.31	19.31	19.31
7	11.88	11.88	11.88	12.04	12.19	12.36	12.36	12.19	12.04	11.88	11.88	11.88
8	6.51	6.51	6.51	6.66	7.91	9.84	10.33	9.71	7.49	6.68	6.51	6.51
9	8.20	8.20	8.20	8.64	9.00	10.06	10.29	9.69	9.14	8.38	8.20	8.20
10	0.85	0.85	0.85	0.98	1.10	1.15	1.16	1.14	1.06	0.85	0.85	0.85
11	0.85	0.85	0.85	0.98	1.10	1.15	1.16	1.14	1.06	0.85	0.85	0.85
12	0.44	0.44	0.44	0.48	0.52	0.55	0.54	0.51	0.45	0.45	0.44	0.44
13	0.44	0.44	0.44	0.48	0.52	0.55	0.54	0.51	0.45	0.45	0.44	0.44
14	0.48	0.48	0.48	0.52	0.55	0.58	0.59	0.59	0.57	0.53	0.48	0.48
15	0.12	0.12	0.12	0.12	0.12	0.13	0.14	0.13	0.13	0.12	0.12	0.12
16	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
17	1.05	1.05	1.05	1.09	1.19	1.23	1.24	1.23	1.17	1.12	1.05	1.05
18	0.08	0.08	0.08	0.08	0.13	0.48	0.65	0.44	0.09	0.08	0.08	0.08
19	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
20	5.87	5.87	5.99	6.66	6.98	7.11	7.10	6.95	6.61	6.29	5.87	5.87
21	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
22	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04

Table 11. Library values of the monthly roughness length parameter.

Class	Monthly Roughness Length, z_0 (m)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	2.16	2.16	2.16	2.05	1.97	1.91	1.85	1.97	2.01	2.06	2.16	2.16
2	1.99	1.99	1.99	1.96	1.92	1.88	1.82	1.92	1.96	1.99	1.99	1.99
3	2.27	2.27	2.27	2.19	2.11	2.03	2.03	2.11	2.19	2.27	2.27	2.27
4	2.59	2.59	2.59	2.50	2.41	2.28	2.31	2.50	2.55	2.59	2.59	2.59
5	1.26	1.26	1.26	1.32	1.37	1.44	1.49	1.48	1.46	1.40	1.30	1.26
6	2.01	2.01	2.01	1.93	1.86	1.77	1.77	1.86	1.93	2.01	2.01	2.01
7	1.24	1.24	1.24	1.19	1.14	1.09	1.09	1.14	1.19	1.24	1.24	1.24
8	0.97	0.97	0.97	1.03	1.56	1.85	1.70	1.89	1.36	1.03	0.97	0.97
9	1.88	1.88	1.88	1.91	1.80	1.48	1.41	1.59	1.76	1.98	1.88	1.88
10	0.14	0.14	0.14	0.20	0.26	0.25	0.25	0.26	0.24	0.14	0.14	0.14
11	0.14	0.14	0.14	0.20	0.26	0.25	0.25	0.26	0.24	0.14	0.14	0.14
12	0.08	0.08	0.08	0.10	0.12	0.13	0.13	0.11	0.09	0.09	0.08	0.08
13	0.08	0.08	0.08	0.10	0.12	0.13	0.13	0.11	0.09	0.09	0.08	0.08
14	0.10	0.10	0.10	0.12	0.14	0.13	0.12	0.12	0.13	0.13	0.10	0.10
15	0.03	0.03	0.03	0.03	0.03	0.04	0.04	0.04	0.04	0.03	0.03	0.03
16	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
17	0.23	0.23	0.23	0.25	0.24	0.23	0.23	0.23	0.25	0.27	0.23	0.23
18	0.01	0.01	0.02	0.02	0.03	0.09	0.11	0.09	0.03	0.02	0.01	0.01
19	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
20	1.30	1.30	1.36	1.30	1.21	1.17	1.17	1.21	1.32	1.41	1.30	1.30
21	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
22	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005

4 Rooting Depth

The rooting depths for the various land cover classes are not described in the vegetation library but are instead supplied in the vegetation parameter file. In this manner rooting depth is specified individually for each VIC computational cell, presumably to capture spatial variation in rooting depth among and within the land cover classes. However, there is insufficient information with which to characterize the spatial variability of rooting depth within land cover classes, so parameters are assumed spatially uniform for each class. However, the parametrization of rooting depth does explicitly consider variability between land cover classes and vegetation types.

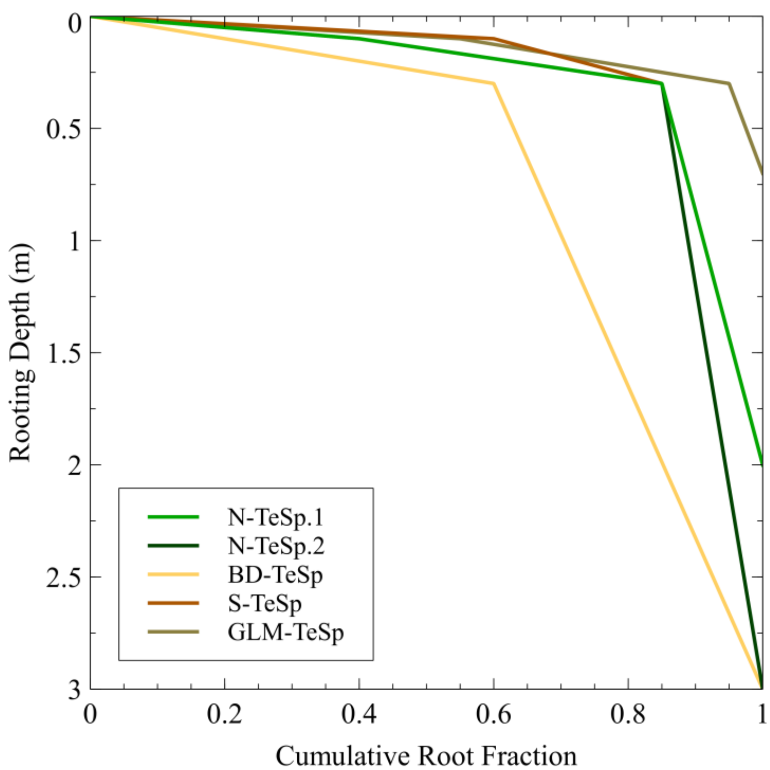


Figure 13. Root zone distributions for select land cover classes.

Rooting depth parameter values were adapted from data given by Jackson et al. (1996) and Schenk and Jackson (2002). Rooting depth parameters describe the distribution of plant roots with depth, where the root zone is divided into three layers. Consequently, a total of six parameters are used: the parameters *RTHICK1*, *RTHICK2*, and *RTHICK3* describe the thickness of root zone layers 1, 2, and 3, respectively, and the parameters *RFRAC1*, *RFRAC2*, and *RFRAC3* describe the fraction of roots within root zone layers 1, 2 and 3, respectively. In general, the parameters reflect that trees are more deeply rooted than shrubs, which are more deeply rooted than tundra vegetation (Figure 13). For the Barren, Water and Ice land cover classes rooting depth parameters are not applicable and dummy values are set such that all 'roots' are in the first 0.1m (i.e. *RDEPTH1*=0.1m and *RFRAC1*=1.0). Note that the total depth of the root zone need not equal the total depth of the soil layer; if the two depths are not equal then the root zone distribution is scaled to equal total soil depth. Final rooting depth parameter values are given in Table 12.

Table 12. Root zone distribution parameters.

Class	RTHICK1	RTHICK2	RTHICK3	RFRAC1	RFRAC2	RFRCA3
1	0.10	0.20	1.70	0.40	0.45	0.15
2	0.10	0.20	2.70	0.40	0.45	0.15
3	0.10	0.20	2.70	0.20	0.40	0.40
4	0.10	0.20	2.70	0.20	0.40	0.40
5	0.10	0.20	1.70	0.40	0.45	0.15
6	0.10	0.20	2.70	0.35	0.40	0.25
7	0.10	0.20	2.70	0.30	0.45	0.25
8	0.10	0.20	2.70	0.20	0.40	0.40
9	0.10	0.20	2.70	0.20	0.40	0.40
10	0.10	0.20	1.70	0.35	0.40	0.25
11	0.10	0.20	1.70	0.60	0.25	0.15
12	0.10	0.20	1.70	0.35	0.40	0.25
13	0.10	0.20	1.70	0.60	0.25	0.15
14	0.10	0.20	0.40	0.55	0.40	0.05
15	0.10	0.20	0.40	0.55	0.40	0.05
16	0.10	0.20	0.10	0.80	0.15	0.05
17	0.10	0.20	0.10	0.80	0.15	0.05
18	0.10	0.20	1.00	0.30	0.40	0.30
19	0.10	0.10	0.10	1.00	0.00	0.00
20	0.10	0.20	0.40	0.55	0.40	0.05
21	0.10	0.10	0.10	1.00	0.00	0.00
22	0.10	0.10	0.10	1.00	0.00	0.00

5 Sensitivity Analysis

Due to the paucity of data, many of the vegetation parameters remain highly uncertain. Consequently, a sensitivity analysis was conducted to ascertain the effects of parameter uncertainty on hydrologic model output. This should guide the understanding of how uncertainty in the selection of appropriate vegetation parameters may affect VIC model results. Details of the sensitivity analysis are provided as Appendix A.

6 Topography

Hydrologic processes are sensitive to spatial variation in topography, particularly as it affects such processes as temperature lapse rates, precipitation amount (e.g., orography) and phase, and solar loading. Topographic variability is considered by directly parameterizing the effect of elevation only; other topographic characteristics, such as slope and aspect, are currently ignored in this latest version of VIC (although this is something for future consideration). Sub-grid elevation variability in the VIC model is parametrized by sub-dividing each grid cell into elevation bands. These bands, in conjunction with user-specified precipitation and temperature gradients, are then used to determine the elevation-based sub-grid spatial variability in forcing temperature and precipitation. Elevation bands do not contain spatially explicit information in that discontinuous areas within certain topographic range are lumped into a single band. Elevation bands have been constructed based on 100-, 200- and 500-m elevation intervals.

6.1 Source Data

Topographic parameterization is based on the Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010) (Danielson and Gesch 2011). GMTED2010 is an enhanced digital elevation model developed as a collaborative effort between the U.S. Geological Survey and the National Geospatial-Intelligence Agency (NGA). This product provides global coverage of all land areas from latitude 84°N to 56°S for most products and from 84°N to 90°S for some products. The GMTED2010 product suite contains seven new raster elevation products for each of the 30-, 15-, and 7.5-arc-second spatial resolutions and incorporates the current best available global elevation data. The new elevation products have been produced using the following aggregation methods: minimum elevation, maximum elevation, mean elevation, median elevation, standard deviation of elevation, systematic subsample, and breakline emphasis. The global aggregated vertical accuracy of GMTED2010 can be summarized in terms of the resolution and RMSE of the products with respect to a global set of control points (estimated global accuracy of 6 m RMSE) provided by the National Geospatial-Intelligence Agency

(NGA). At 30 arc-seconds, the GMTED2010 RMSE range is between 25 and 42 meters; at 15 arc-seconds, the RMSE range is between 29 and 32 meters; and at 7.5 arc-seconds, the RMSE range is between 26 and 30 meters. The elevation data were accessed using the GMTED2010 Viewer (http://topotools.cr.usgs.gov/gmted_viewer/viewer.htm).

6.2 Processing

All topographic parameterization is based on processing of the 7.5 arc-second mean elevation product. Prior to detailed parametrization, the DEM was clipped to a domain bounded by 40°N to 72°N and 169°W to 101°W, which is the maximum extent of the VIC application area. This clipped DEM is shown in Figure 14. The raw study area hypsometry and additional statistics are given as Figure 15.

The following GIS processing steps were used to generate elevation bands from the source digital elevation model:

1) Reclassification of the DEM into 100-, 200- and 500-m intervals. All elevation ranges begin from a base elevation of zero metres. Elevation reclassification is detailed in Table 13.
2) Convert reclassified elevation grids to polygon features.
3) Intersect elevation band polygon features with VIC computational mesh.
4) Dissolve resultant polygons by common cell and elevation band identifiers.
5) Calculate median elevation for each individual cell-band polygon.

The resultant post-processed products are a set of three spatial polygon features in ESRI shapefile format representing the study domain in 100-, 200- and 500-m elevation bands per VIC computational cell. These features are then used in subsequent processing steps, in combination with vegetation cover (§2), to generate VIC hydrologic response units (HRUs) (§7).

In previous applications of VIC elevation bands were specified by dividing the grid cell into bands of roughly equal area, while respecting the constraints that the band interval must be less than some user-specified range (e.g., $\Delta z \leq 500$m) and the maximum number of bands was limited (usually five). Unlike previous applications, herein we set fixed elevation intervals (Δz =100, 200 or 500m) and allow the area of each elevation band to vary based on local cell hypsometry. The number of bands in each cell is strictly a function of the elevation range and is not constrained.

6.3 Results

Given a maximum elevation of 6146 m (Denali), the study domain has been classified into 62, 31 and 13 100-, 200- and 500-m elevation bands, respectively (Table 13). The resultant number of 100-m elevation bands per VIC grid cell is mapped in Figure 16 and the distribution is given by Figure 17. Throughout the entire study domain, the number of 100-m elevation bands per cell ranges from 1 to 38, with a median of two bands per cell. For the 200- and 500-m bands, the maximum number of bands per cell is 19 and 8, respectively, with a median of one band per cell for both cases. For 90% of the study domain, VIC cells contain ten or less 100-m elevation bands. The study area hypsometry based on 100-, 200-, and 500-m vertical resolution are compared in Figure 18, where all three match the hypsometry of the original

GMTED2010 DEM very well (Table 14). Nevertheless, the choice of using a fixed vertical resolution does result in a 'segmented' structure to the hypsometry based on the elevation bands.

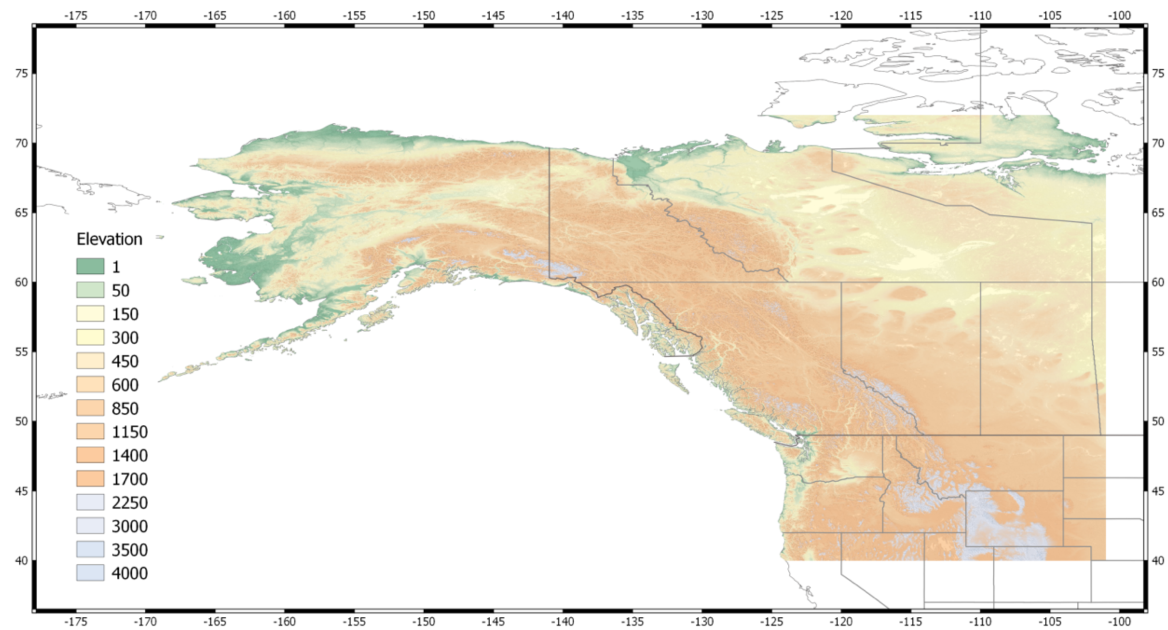


Figure 14. GMTED 2010 7.5 arc-seconds digital elevation model for north-western North America.

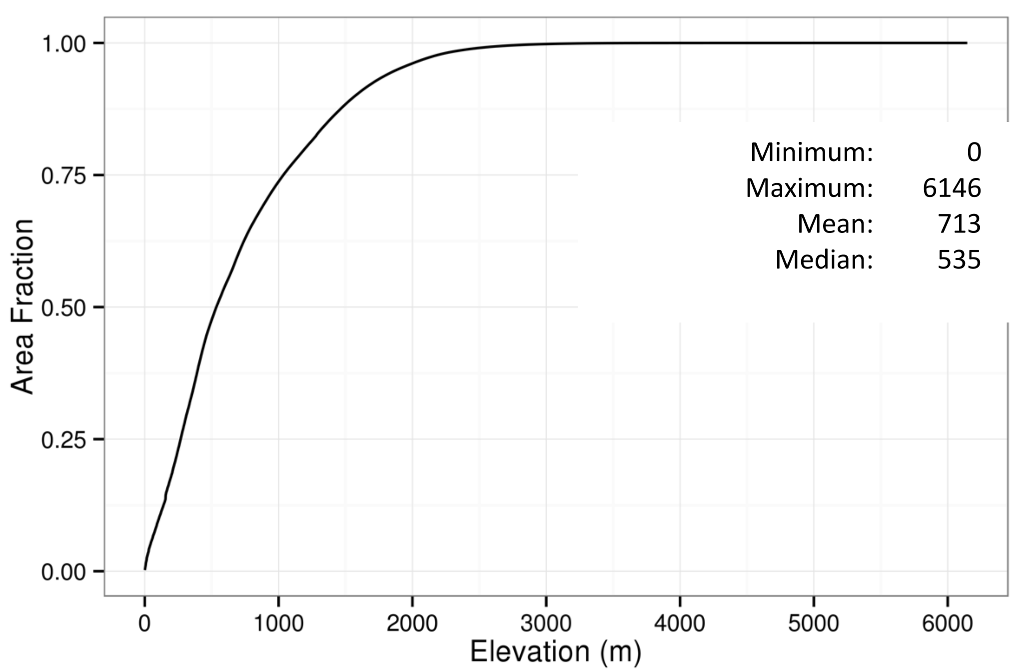


Figure 15. Study domain hypsometry and elevation statistics based on 7.5 arc-second GMTED 2010 digitial elevation model.

Table 13.Elevation reclassification into 100-, 200- and 500-m bands

Z_{lower} (>=)	Z_{upper} (<)	Band ID 100m	Band ID 200m	Band ID 500m	|	Z_{lower} (>=)	Z_{upper} (<)	Band ID 100m	Band ID 200m	Band ID 500m
0	100	50	100	250	|	3200	3300	3250	3300	3250
100	200	150			|	3300	3400	3350		
200	300	250	300		|	3400	3500	3450	3500	
300	400	350			|	3500	3600	3550		3750
400	500	450	500		|	3600	3700	3650	3700	
500	600	550		750	|	3700	3800	3750		
600	700	650	700		|	3800	3900	3850	3900	
700	800	750			|	3900	4000	3950		
800	900	850	900		|	4000	4100	4050	4100	4250
900	1000	950			|	4100	4200	4150		
1000	1100	1050	1100	1250	|	4200	4300	4250	4300	
1100	1200	1150			|	4300	4400	4350		
1200	1300	1250	1300		|	4400	4500	4450	4500	
1300	1400	1350			|	4500	4600	4550		4750
1400	1500	1450	1500		|	4600	4700	4650	4700	
1500	1600	1550		1750	|	4700	4800	4750		
1600	1700	1650	1700		|	4800	4900	4850	4900	
1700	1800	1750			|	4900	5000	4950		
1800	1900	1850	1900		|	5000	5100	5050	5100	5250
1900	2000	1950			|	5100	5200	5150		
2000	2100	2050	2100	2250	|	5200	5300	5250	5300	
2100	2200	2150			|	5300	5400	5350		
2200	2300	2250	2300		|	5400	5500	5450	5500	
2300	2400	2350			|	5500	5600	5550		5750
2400	2500	2450	2500		|	5600	5700	5650	5700	
2500	2600	2550		2750	|	5700	5800	5750		
2600	2700	2650	2700		|	5800	5900	5850	5900	
2700	2800	2750			|	5900	6000	5950		
2800	2900	2850	2900		|	6000	6100	6050	6100	6250
2900	3000	2950			|	6100	6200	6150		
3000	3100	3050	3100	3250	|					
3100	3200	3150			|					

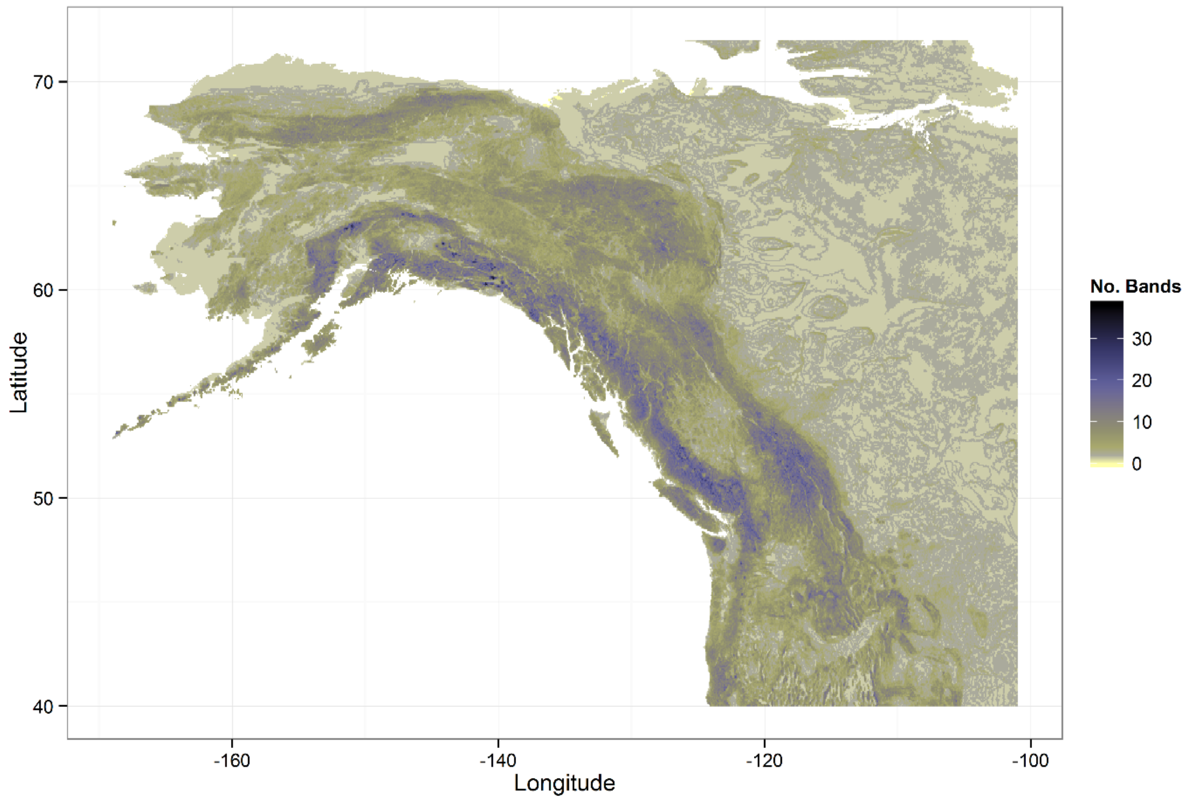


Figure 16. Number of 100-m elevation bands per 1/16-dgeree VIC model cell.

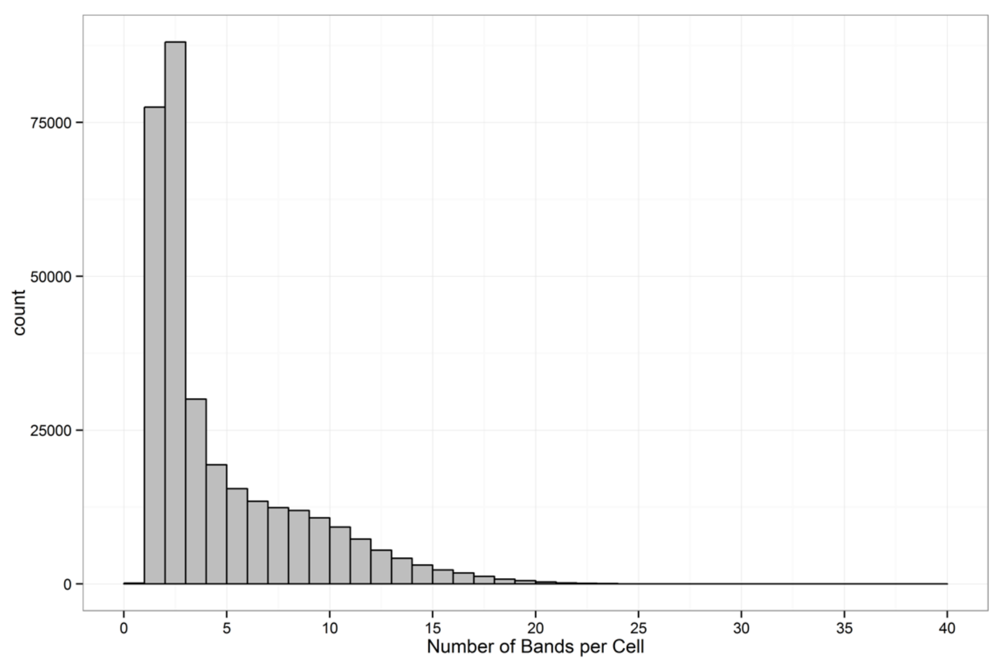


Figure 17. Histogram of the number of 100-m elevation bands per VIC model cell.

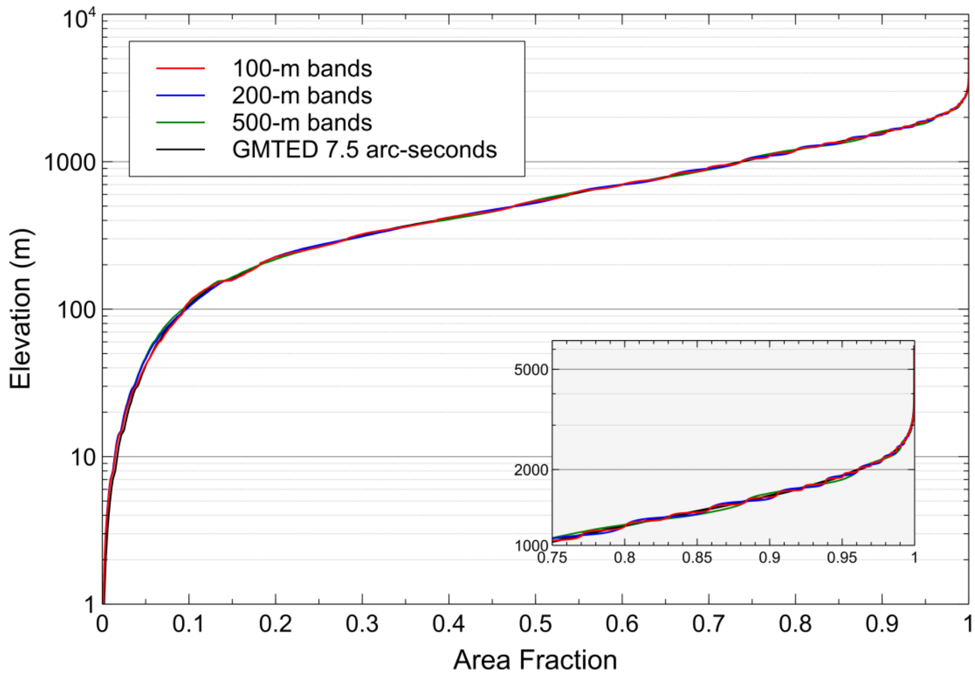


Figure 18. Study area hypsometry based on 100-, 200- and 500-m elevation bands compared to the original 7.5 arc-seconds GMTED2010 DEM.

Table 14. Comparison of elevation hypsometry for select quantiles

Cumulative Area	Elevation Quantile (m)			
	7.5" GMTED2010	100-m Bands	200-m Bands	500-m Bands
0.1	106	111	103	109
0.2	218	225	226	217
0.3	316	322	311	311
0.4	413	419	419	406
0.5	534	540	525	546
0.6	698	695	697	701
0.7	903	914	898	882
0.8	1197	1187	1187	1208
0.9	1572	1554	1531	1610
1.0	6146	6129	6063	6063

7 Vegetation and Snowband Parameter

7.1 Hydrologic Response Units

Sub-grid variability in the VIC model is described using Hydrologic Response Units (HRUs), which are computational elements that are considered homogeneous from a hydro-climatological perspective. In the generation 2 application of the model, HRUs are created based on land cover classification and elevation, i.e., landscape elements are grouped into hydro-climatically homogeneous units if they have the same land cover and are within the same elevation range. Sub-grid variability is determined by dividing each VIC grid cell into a collection of HRUs, where the HRU acts as the fundamental computational element of the model. The number of HRUs, and hence the effective model resolution, is then governed by the fidelity of the land cover classification (i.e., number of classes) and the vertical resolution employed (i.e., band discretization). Note that HRUs do not retain any information on the original spatial organization of landscape elements as all areas of the same vegetation class within an elevation range are lumped together into a single HRU.

7.2 Processing HRUs

HRUs are generated by spatially intersecting land cover classes (§2) with elevation bands (§6) within each VIC-GL grid cell. The process of generating HRUs is detailed in Schnorbus (2020) and is based on the scripts located in the repository https://github.com/mschnorb/vicHRUParameters. Only a summary Is presented here.

An important step in the process is the creation of an HRU table, which describes the HRUs (class and elevation band) for each VIC-GL computational cell. This process produces an HRU table with one record for each unique HRU, which contains the following fields:

1. CELL_ID: unique grid cell identifier from the VIC-GL soil parameter file, e.g., 36874;
2. BAND_ID: non-unique ID given as nominal band elevation from Table 13; e.g., 1100;
3. POLY_ID: non-unique ID for each cell-band intersection as concatenation of CELL_ID and BAND_ID, e.g., 36874_1100;
4. CLASS: vegetation class from Table 1;
5. ELEVATION: actual median elevation of elevation band derived from DEM; and
6. AREA: area of HRU polygon in m^2.

An example of a raw HRU table is given in Table 15. This example is for a study area encompassing the Peyto Glacier in the Rocky Mountains wherein the domain is made up of two VIC cells (354439 and 354440) divided into 200-m elevation band and containing four land cover classes (11, 19, 21 and 22.

Table 15. HRU table for the Peyto Glacier study area, which is based on two VIC cell, 200-m bands and four vegetation classes.

CELL_ID	BAND_ID	POLY_ID	CLASS	ELEVATION	AREA
354439	2100	354439_2100	11	2146	341845.117
354439	2100	354439_2100	19	2146	1128631.822
354439	2300	354439_2300	11	2290	137862.973
354439	2300	354439_2300	19	2290	3291821.385
354439	2300	354439_2300	22	2290	145790.229
354439	2500	354439_2500	19	2516	4334692.718
354439	2500	354439_2500	22	2516	3216984.208
354439	2700	354439_2700	19	2672	4772220.642
354439	2700	354439_2700	22	2672	7927036.028
354439	2900	354439_2900	19	2857	2845176.541
354439	2900	354439_2900	22	2857	1632803.531
354439	3100	354439_3100	19	3032	263951.419
354439	3100	354439_3100	22	3032	36786.081
354440	2100	354440_2100	19	2177	629040.292
354440	2100	354440_2100	22	2177	205949.327
354440	2300	354440_2300	19	2294	2837992.551
354440	2300	354440_2300	21	2294	244726.385
354440	2300	354440_2300	22	2294	893128.031
354440	2500	354440_2500	19	2526	5486822.465
354440	2500	354440_2500	21	2526	17472.687
354440	2500	354440_2500	22	2526	4253578.105
354440	2700	354440_2700	19	2684	5221417.936
354440	2700	354440_2700	22	2684	7813618.023
354440	2900	354440_2900	19	2859	1486004.648
354440	2900	354440_2900	22	2859	820008.599
354440	3100	354440_3100	19	3038	167064.572

7.3 HRU Summary

Figure 19 shows the discretization of land cover classes by elevation for the Bull River basin using 100-, 200- and 500-m elevation bands. Clearly the use of 100-m bands provides the greatest detail in terms of basin hypsometry and land cover distribution, information which becomes progressively coarser when going to 200- and 500-m bands. On the other hand, the total number of HRUs and hence the computational burden, decreases when the vertical resolution is decreased. Based on the results of a sensitivity analysis we have opted to use a 200-m vertical band resolution in the current VIC application.

This represents a very small sacrifice in terms of simulation accuracy when compared to using 100-m bands but provides substantial advantages in computational efficiency.

The spatial distribution of the number of land cover classes, 200-m elevation bands and HRUs for three example study areas, the Peace, Fraser, and Columbia basins, is given in Figure 20. The amount of vegetation diversity, or number of different vegetation types per cell, ranges considerably between 1 and 13. The degree of relief, or number of elevation bands, also shows a large range, varying from a single band to as many as 16 bands per cell. The resulting distribution of the number of HRUs per cell also displays a large range, with very small values (as low as 1) is areas of low diversity and/or low relief to as high as 64 in areas of high diversity and/or high relief. The largest number of HRUs tends to be found in the Rockies, Columbia, and Coast Mountains, whereas the lowest values are found throughout the Boreal Plains (Peace), the Interior Plateau (Fraser), the Columbia Plateau (Columbia), and the Snake River Plain (Columbia). The resulting distribution of land cover by 200-m elevation bands for three major drainage basins is given in Figure 21.

7.4 Vegetation and Snowband Parameter Files

The vegetation parameter and elevation band input files are generated by processing the information from the HRU table in combination with the root zone fractions (§4). The reader is referred to Schnorbus (2020) for a detailed description of how to generate each parameter files using the scripts located in the repository https://github.com/mschnorb/vicHRUParameters. Examples for both the vegetation and elevation band parameter files are given in Appendix B.

a)

100-m Bands
No. HRUs = 2530

b)

200-m Bands
No. HRUs = 1440

c)

500-m Bands
No. HRUs = 796

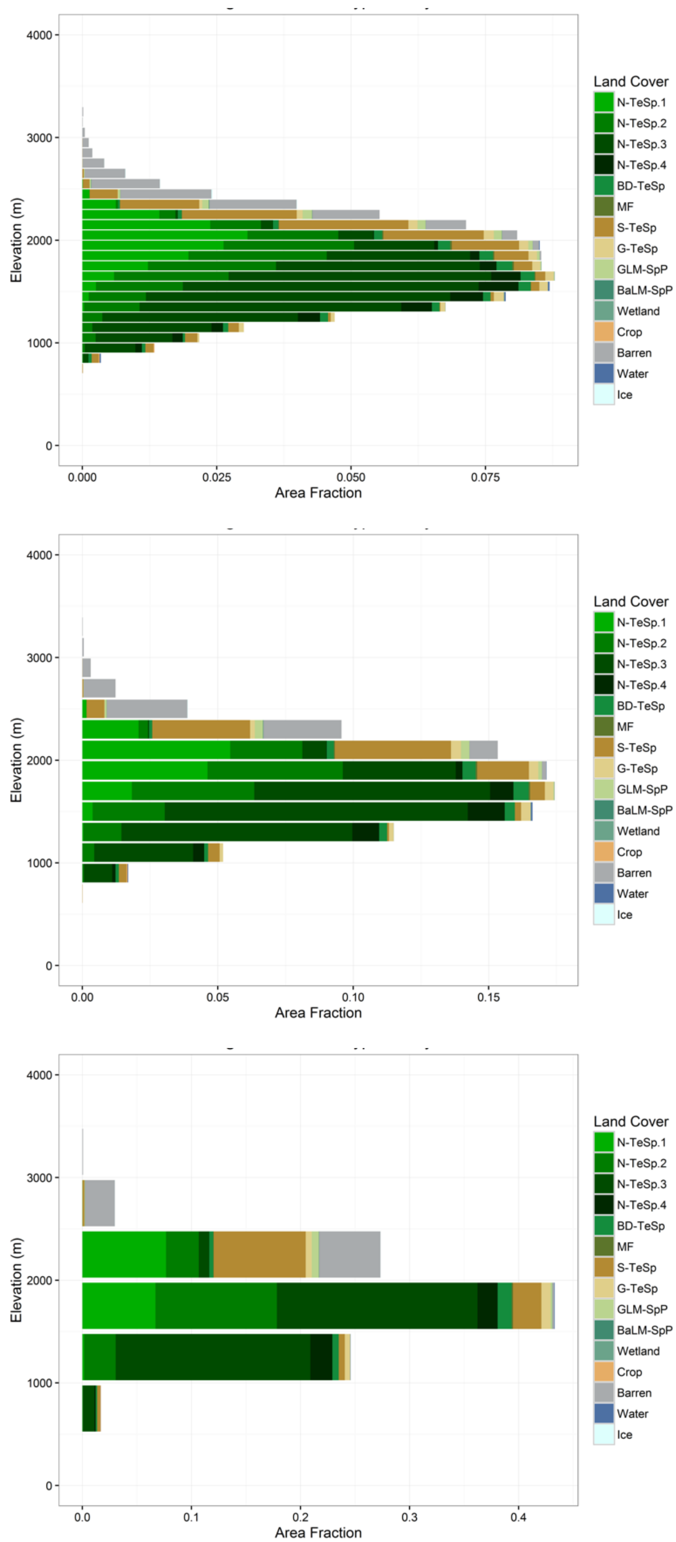


Figure 19. Effect of elevation resolution on land cover variability.

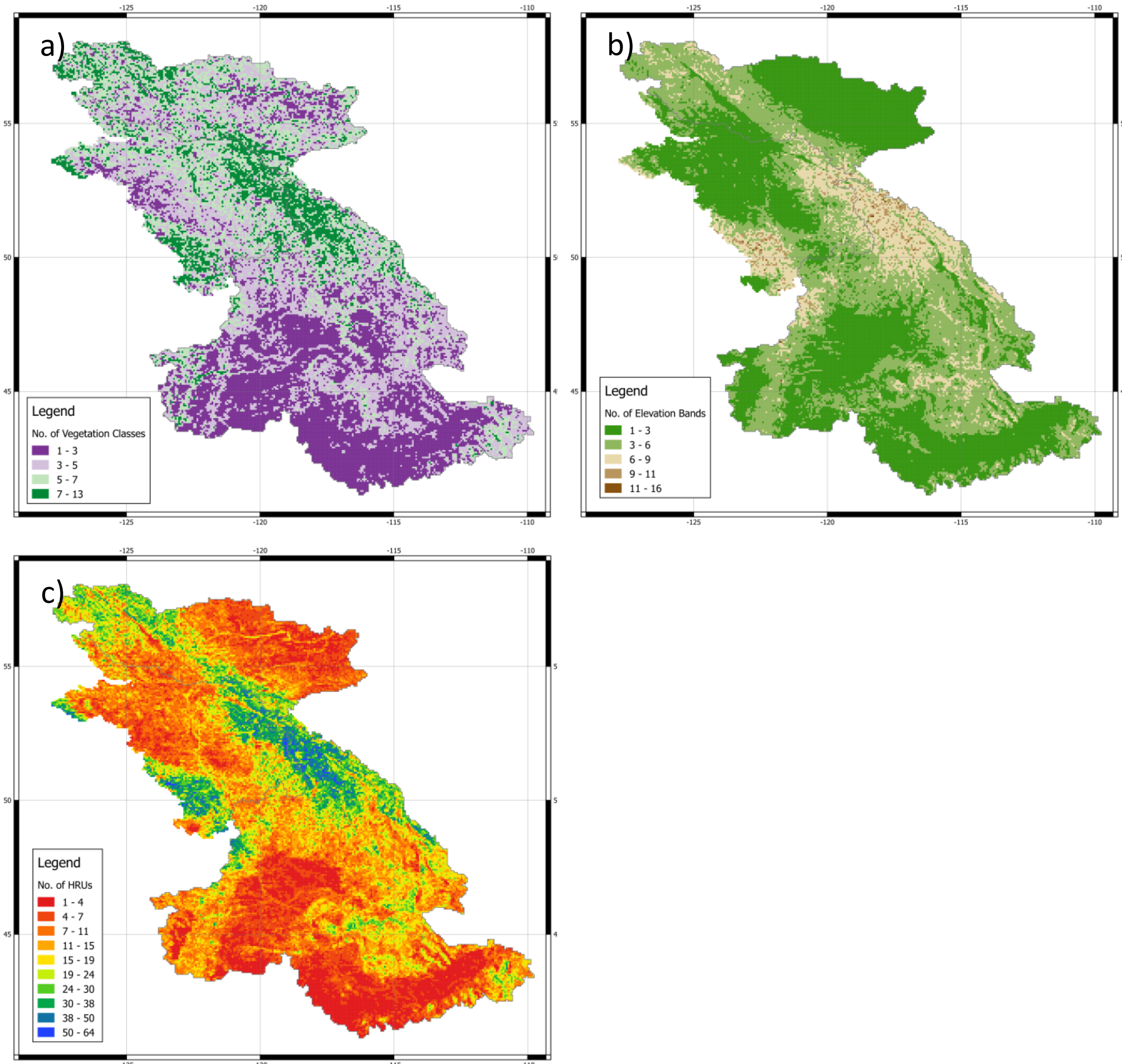
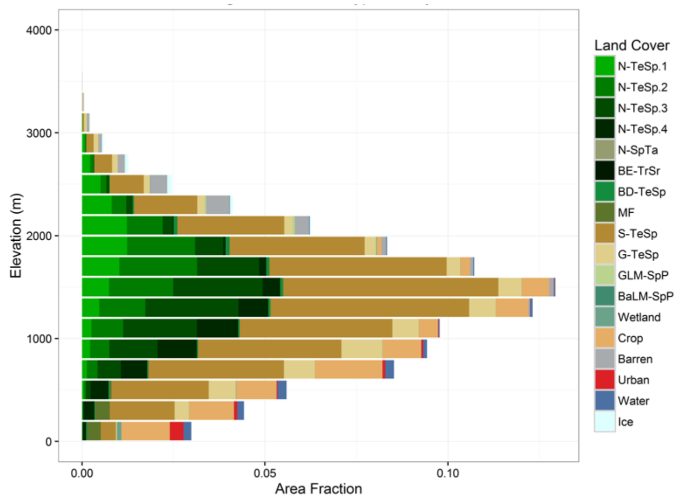


Figure 20. Spatial distribution of the number of a) vegetation classes, b) 200-m elevation bands, and c) hydrologic response units per VIC cell for the Peace, Fraser and Columbia study areas.

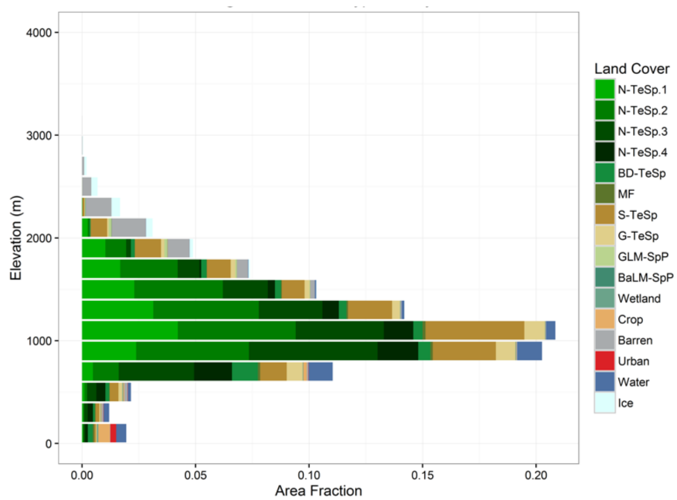
a)

Columbia
Area = 696417 km^2
Minimum elevation = 0 m
Maximum elevation = 4268 m
Maximum number of bands per cell = 14
Number of land cover classes = 18
Number of cells = 20814
Number of HRUs = 267299



b)

Fraser
Area = 250238 km^2
Minimum elevation = 0 m
Maximum elevation = 3845 m
Maximum number of bands per cell = 16
Number of land cover classes = 16
Number of cells = 8452
Number of HRUs = 144643



c)

Peace
Area = 203969 km^2
Minimum elevation = 318 m
Maximum elevation = 3276 m
Maximum number of bands per cell = 11
Number of land cover classes = 17
Number of cells = 7485
Number of HRUs = 101348

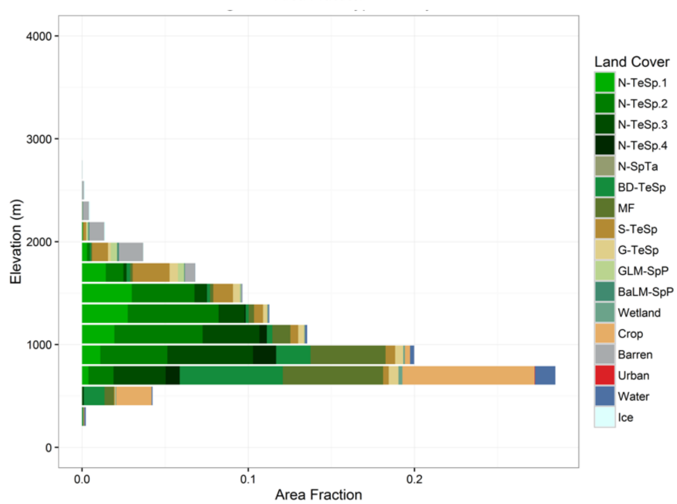


Figure 21. Distribution of vegetation by 200-m elevation bands with summary statistics for the a) Columbia at outlet, b) Fraser at outlet, and c) Peace (at Peace River, AB) drainages.

8 References

Amiro, B. D., 1990: Drag coefficients and turbulence spectra within three boreal forest canopies. *Bound.-Layer Meteorol.*, **52**, 227–246, https://doi.org/10.1007/BF00122088.

Baird, A. J., and R. L. Wilby, 1999: *Eco-hydrology*. Routledge, 402 pp.

Baret, F., M. Weiss, R. Lacaze, F. Camacho, H. Makhmara, P. Pacholcyzk, and B. Smets, 2013: GEOV1: LAI and FAPAR essential climate variables and FCOVER global time series capitalizing over existing products. Part1: Principles of development and production. *Remote Sens. Environ.*, **137**, 299–309, https://doi.org/10.1016/j.rse.2012.12.027.

Camacho, F., J. Cernicharo, R. Lacaze, F. Baret, and M. Weiss, 2013: GEOV1: LAI, FAPAR essential climate variables and FCOVER global time series capitalizing over existing products. Part 2: Validation and intercomparison with reference products. *Remote Sens. Environ.*, **137**, 310–329, https://doi.org/10.1016/j.rse.2013.02.030.

Campbell, G. S., and J. M. Norman, 1998: *An introduction to environmental biophysics*. Springer, 286 pp.

Cavazzuti, M., 2013: *Optimization Methods - From Theory to Design*. Springer-Verlag, 262 pp.

Choudhury, B. J., and J. L. Monteith, 1988: A four-layer model for the heat budget of homogeneous land surfaces. *Q. J. R. Meteorol. Soc.*, **114**, 373–398, https://doi.org/10.1002/qj.49711448006.

Christophe, D., and S. Petr, 2015: *randtoolbox: Generating and Testing Random Numbers*.

Danielson, J. J., and D. B. Gesch, 2011: *Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010)*. U.S. Geological Survey, http://pubs.usgs.gov/of/2011/1073/pdf/of2011-1073.pdf (Accessed November 2, 2015).

Dickinson, R. E., 1983: Land surface processes and climate - surface albedos and energy balance. *Theory of Climate*, B. Saltzman, Ed., Vol. 25 of *Advances in Geophysics*, Academic Press, Inc., 305–353.

Dickinson, R. E., A. Henderson-Sellers, C. Rosenzweig, and P. J. Sellers, 1991: Evapotranspiration Models with Canopy Resistance for Use in Climate Models - A Review. *Agric. For. Meteorol.*, **54**, 373–388, https://doi.org/10.1016/0168-1923(91)90014-H.

Dorman, J. L., and P. J. Sellers, 1989: A Global Climatology of Albedo, Roughness Length and Stomatal Resistance for Atmospheric General Circulation Models as Represented by the Simple Biosphere Model (SiB). *J. Appl. Meteorol.*, **28**, 833–855, https://doi.org/10.1175/1520-0450(1989)028<0833:AGCOAR>2.0.CO;2.

Ducoudré, N. I., K. Laval, and A. Perrier, 1993: SECHIBA, a New Set of Parameterizations of the Hydrologic Exchanges at the Land-Atmosphere Interface within the LMD Atmospheric General

Circulation Model. *J. Clim.*, **6**, 248–273, https://doi.org/10.1175/1520-0442(1993)006<0248:SANSOP>2.0.CO;2.

Jackson, R. B., J. Canadell, J. R. Ehleringer, H. A. Mooney, O. E. Sala, and E. D. Schulze, 1996: A global analysis of root distributions for terrestrial biomes. *Oecologia*, **108**, 389–411, https://doi.org/10.1007/BF00333714.

Kondo, J., 1971: Relationship between the roughness coefficient and other aerodynamic parameters. *J. Meteorol. Soc. Jpn. Ser II*, **49**, 121–124.

Lafleur, P., 1988: Leaf conductance of four species growing in a subarctic marsh. *Can. J. Bot.*, **66**, 1367–1375, https://doi.org/10.1139/b88-192.

Liang, S., 2001: Narrowband to broadband conversions of land surface albedo I: Algorithms. *Remote Sens. Environ.*, **76**, 213–238, https://doi.org/10.1016/S0034-4257(00)00205-4.

Liang, X., D. P. Lettenmaier, E. F. Wood, and S. J. Burges, 1994: A simple hydrologically based model of land-surface water and energy fluxes for general-circulation models. *J. Geophys. Res.-Atmospheres*, **99**, 14415–14428, https://doi.org/10.1029/94JD00483.

Munro, D. S., 1989: Stomatal conductances and surface conductance modelling in a mixed wetland forest. *Agric. For. Meteorol.*, **48**, 235–249, https://doi.org/10.1016/0168-1923(89)90071-3.

Nychka, D., R. Furrer, and S. Sain, 2015: *fields: Tools for Spatial Data*.

Pfeffer, W. T., and Coauthors, 2014: The Randolph Glacier Inventory: A globally complete inventory of glaciers. *J. Glaciol.*, **221**, 537–552, https://doi.org/10.3189/2014JoG13J176.

Produced by Natural Resources Canada/ The Canada Centre for Mapping and Earth Observation (NRCan/CCMEO), United States Geological Survey (USGS), Insituto Nacional de Estadística y Geografía (INEGI), Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (CONABIO), and Comisión Nacional Forestal (CONAFOR), 2013: 2010 North American Land Cover at 250 m spatial resolution.

R Core Team, 2016: *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing,.

Sabziparvar, A. A., 2008: A simple formula for estimating global solar radiation in central arid deserts of Iran. *Renew. Energy*, **33**, 1002–1010, https://doi.org/10.1016/j.renene.2007.06.015.

Schenk, H. J., and R. B. Jackson, 2002: The global biogeography of roots. *Ecol. Monogr.*, **72**, 311–328, https://doi.org/10.1890/0012-9615(2002)072[0311:TGBOR]2.0.CO;2.

Schnorbus, M. A., 2020: *VIC-Glacier (VIC-GL) Vegetation and Band Parameter Files*. Pacific Climate Impacts Consortium, University of Victoria, pp. 14.

Schulze, E.-D., F. M. Kelliher, C. Korner, J. Lloyd, and R. Leuning, 1994: Relationships among maximum stomatal conductance, ecosystem surface conductance, carbon assimilation rate, and plant nitrogen nutrition: A global ecology scaling exercise. *Annu. Rev. Ecol. Syst.*, **25**, 629–660.

Sellers, P. J., 1985: Canopy reflectance, photosynthesis and transpiration. *Int. J. Remote Sens.*, **6**, 1335–1372, https://doi.org/10.1080/01431168508948283.

Simard, M., N. Pinto, J. B. Fisher, and A. Baccini, 2011: Mapping forest canopy height globally with spaceborne lidar. *J. Geophys. Res. Biogeosciences*, **116**, G04021, https://doi.org/10.1029/2011JG001708.

Toney, C., and M. C. Reeves, 2009: Equations to convert compacted crown ratio to uncompacted crown ratio for trees in the Interior West. *West. J. Appl. For.*, **24**, 76–82.

Wigmosta, M. S., L. W. Vail, and D. P. Lettenmaier, 1994: A distributed hydrology-vegetation model for complex terrain. *Water Resour. Res.*, **30**, 1665–1679, https://doi.org/10.1029/94WR0043.

Appendix A

Vegetation Sensitivity Analysis

Sensitivity analysis was applied using the latest stable release (at time of writing) of the PCIC version of the VIC model (VIC Glacier, released August 26, 2015). The analysis was conducted over the Bull River drainage basin above the Bull River near Wardner Water Survey of Canada (WSC) gauging site (08NG002). The Bull River, which is a tributary of the Kootenay River, drains approximately 1520 km^2 in the Columbia Mountains in southeastern British Columbia. The vegetation cover and hypsometry of the study area are shown in Figure 22. The basin spans and elevation range of 800 to 3260 m. Vegetation in is dominated by the temperate or sub-polar needle leaf classes N-TeSp.1, N-TeSp.2 and N-TeSp.3, which account for 14%, 17% and 38% of basin area, respectively. The shrub and open or barren ground vegetation classes dominate at higher elevations.

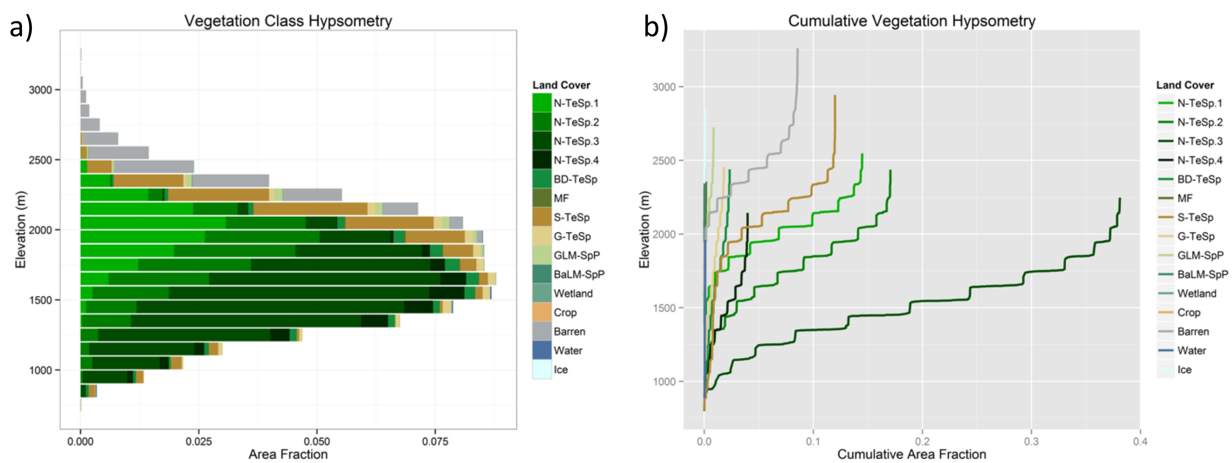


Figure 22. Vegetation distribution for the Bull River basin, showing (a) vegetation fraction, and (b) cumulative vegetation by elevation.

Method

The method follows the classic Design of Experiment approach (e.g. Cavazzuti 2013). The experiment is designed such that the sensitivity of the VIC model is assessed by quantifying the change in several *response variables* (i.e., VIC output variables) to changes in several *factors* (i.e., vegetation parameters). The design space (or range of variability) was set by sampling the various parameters within a scaled range of 0.2 to 2.0 (i.e., parameter value *p* varies from 0.2*p* to 2*p*). To maintain physically plausible values however, the upper scaling range for several parameters had to be lowered. The parameters selected for sensitivity analysis and the final scaling ranges are given in Table 16. Note that the parameter names used here differ from those used in Sections 0 and 0 (see Table 16 for details). Special care had to be taken when scaling root fractions (RFRAC) to ensure that the total root fraction always equals one. Hence, root fractions were scaled as follows:

$$RFRAC3' = s \cdot RFRAC3 \quad (14)$$

subject to

$$\frac{RFRAC1'}{RFRAC1} = \frac{RFRAC2'}{RFRAC2} \quad (15)$$

and

$$RFRAC1' = 1 - RFRAC2' - RFRAC3', \quad (16)$$

where *RFRACX* is the root fraction for layer *X*, *s* is the scaling factor, and the prime notation denotes the modified value. Note that a single scaling factor is used for all vegetation classes and months (for seasonal parameters), such that the relative inter-class and inter-month variations are maintained as per the baseline values.

Table 16. Parameters selected for sensitivity analysis with scaling limits.

Parameter Name	Scale Min	Scale Max	Description (see Table 4)
RARC	0.2	2.0	r_{arc}
RMIN	0.2	2.0	r_{min}
LAI	0.2	2.0	L
ALBEDO	0.2	1.5	α
ROUGH	0.2	1.25	z_o
DISP	0.2	1.25	d
RGL	0.2	2.0	R_{50}
SOLATN	0.2	1.135	k
WNDATN	0.2	2.0	δ
TRUNK	0.2	1.5	tr
RTHICK3	0.2	2.0	
RFRAC3	0.2	2.0	

The final *sample space* is a *P* x *N* array of values, where *P* is the number of parameters (12) and *N* is the sample size (or number of experiments). For this study, *N* was set to 25. The *P*-dimensional parameter space was sampled using a sobol sequence, which is an efficient quasi-random space-filling technique. The sobol sequence tends to cover the sample space more evenly than the more traditional Latin hypercube approach (e.g. Cavazzuti 2013). This procedure was carried out in R (R Core Team 2016) using the `sobol` function from the `randtoolbox` package (Christophe and Petr 2015). For this experiment the VIC model was run at a daily time step in water balance mode using historical forcing over the period 1/1/1990 to 12/31/2000.

The response for each experiment (or sample) for a given variable was calculated as the relative departure, or anomaly, of the temporal and spatial mean (50 cells) from a baseline value. The baseline value was established using the VIC model run with the original best-estimate vegetation parameters as given in Table 5, Table 7, Table 9, Table 10, Table 11 and Table 12.

The VIC model response over the design space was then approximated by fitting a response surface model to the 25 anomaly values for each variable. As the response variables derive from a deterministic model, the data are considered noise-free, and kriging was used to interpolate a response surface. As the main concern of the sensitivity analysis is to assess the main or first-order effects, we assume a kriging model with a linear trend (also known as universal kriging). The kriging was performed in R using the `Krig` function from the `fields` package (Nychka et al. 2015). Independent response surfaces were estimated for each of the variables listed in Table 17. The sensitivity of each response variable to each parameter was estimated from the individual response surface by calculating the slope of the anomaly given a change in the target parameter, with all other parameters held equal to a value of 1 (i.e., no scaling). Slope values were calculated independently for each parameter for each variable, for a total of *P* x *V* slope values, where *V* is the number of response variables (9 in this case).

Table 17. Response variables for VIC sensitivity analysis.

Variable	Description
EVAP	Total evaporation
EVAP_CANOPY	Evaporation of water intercepted in the vegetation canopy
TRANSP_VEG	Transpiration
WDEW	Water intercepted by vegetation
RUNOFF	Surface runoff
BASEFLOW	Sub-surface runoff
SWE	Snow water equivalent of all snow (ground and canopy)
SNOW_CANOPY	Snow stored in the canopy
SOIL_MOIST	Soil moisture

Results

An example of the relative anomaly response surface, given as a sequence of 2-dimensional panels, is shown for the EVAP variable in Figure 23. In this example, VIC modelled evaporation shows strong sensitivity to the parameters *DISP*, *LAI* and *RMIN*, where increasing *DISP* and *LAI* increases evaporation and increasing *RMIN* decreases evaporation. The estimation of parameter sensitivity as the linear trend in the anomaly with respect to the parameter is generally valid for most parameters.

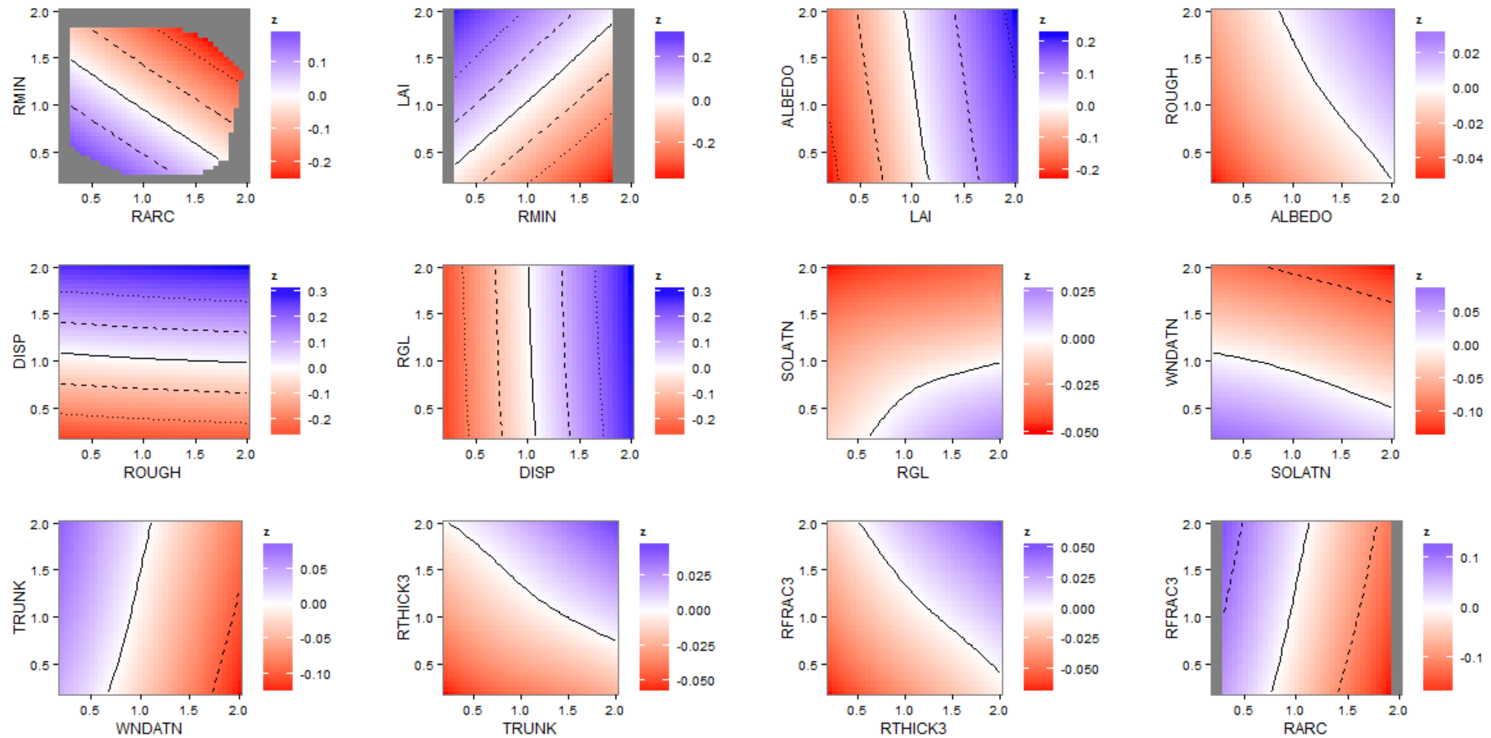


Figure 23. Response surface of EVAP anomaly relative to the baseline experiment shown as a series of 2-dimensional surfaces. The contours represent sensitivity values of 0 (solid), -0.1 to 0.1 (dashed), and -02 to 0.2 (dotted).

Overall model sensitivity for the selected output variables and parameters is summarized in Figure 24. The sensitivity values are interpreted as the relative change in the response variable to a relative change of 100% in the parameter. Most sensitivity values (87%) lie between -0.2 and 0.2, and 67% of values lie between -0.1 and 0.1. That is, for a change in a parameter value of 100%, model output is expected to change by no more than ±20% or ±10%, respectively. Exceptions are the variables SNOW_CANOPY and WDEW; SNOW_CANOPY displays very strong sensitivity ($|b| > 1.0$) to *LAI*, *ROUGH* and *DISP*, and WDEW shows very strong sensitivity to *LAI*. The variable TRANSP_VEG is moderately sensitive ($|b| > 0.2$) to *RMIN*, *LAI*, *ROUGH* and *DISP*. The variables SOIL_MOIST, RUNOFF and SWE exhibit very little sensitivity to variation in any of the parameter values. The VIC model tends to display the most sensitivity to the *LAI*, *ROUGH* and *DISP* parameters, but little sensitivity to the RGL, TRUNK, RTHICK3 and RFRAC3 parameters.

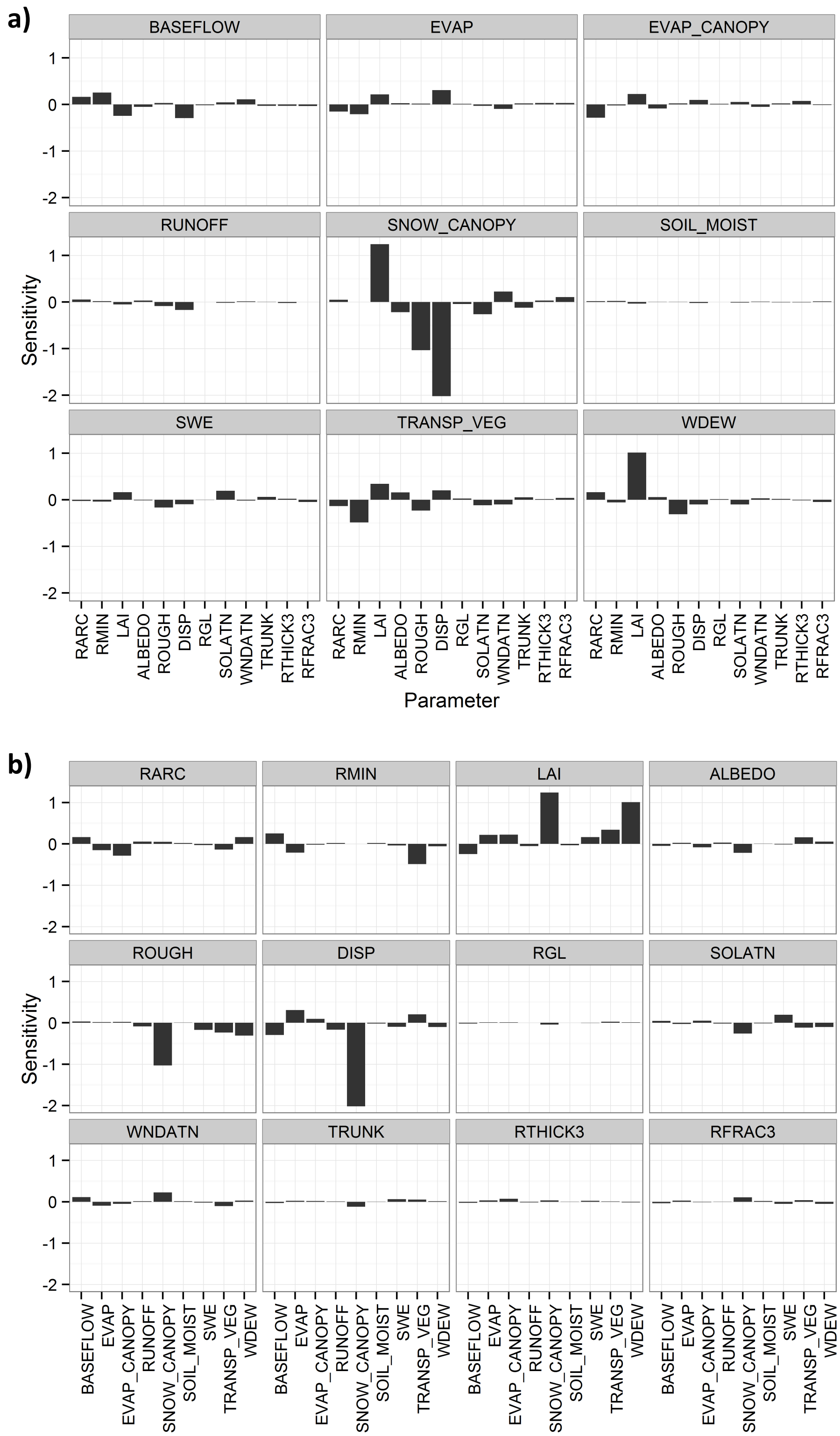


Figure 24. VIC model sensitivity as a function of a) parameter and b) output variable.

Appendix B

Example Input Files

Vegetation Parameter File

vpf_fraser_200_example.txt -- Printed on 22/04/2016, 12:05:45 PM -- Page 1

```
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     3 0.188444902733  0.10  0.20  0.20  0.40  2.70  0.40   0
     4 0.015156234064  0.10  0.20  0.20  0.40  2.70  0.40   0
     8 0.035553885983  0.10  0.20  0.20  0.40  2.70  0.40   0
     9 0.001776322338  0.10  0.20  0.20  0.40  2.70  0.40   0
    13  0.062452771224  0.10  0.60  0.20  0.25  1.70  0.15   0
     3 0.114423545180  0.10  0.20  0.20  0.40  2.70  0.40   1
     4 0.064970890688  0.10  0.20  0.20  0.40  2.70  0.40   1
     8 0.162669439051  0.10  0.20  0.20  0.40  2.70  0.40   1
     9 0.028172368386  0.10  0.20  0.20  0.40  2.70  0.40   1
    13  0.023107205006  0.10  0.60  0.20  0.25  1.70  0.15   1
     2 0.004743260614  0.10  0.40  0.20  0.45  2.70  0.15   2
     3 0.023269323464  0.10  0.20  0.20  0.40  2.70  0.40   2
     8 0.083996273822  0.10  0.20  0.20  0.40  2.70  0.40   2
     9 0.000661219778  0.10  0.20  0.20  0.40  2.70  0.40   2
    11  0.007305143983  0.10  0.60  0.20  0.25  1.70  0.15   2
    13  0.035578296017  0.10  0.60  0.20  0.25  1.70  0.15   2
     1 0.006956043901  0.10  0.40  0.20  0.45  1.70  0.15   3
     2 0.013194932624  0.10  0.40  0.20  0.45  2.70  0.15   3
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     2 0.000650186461  0.10  0.40  0.20  0.45  2.70  0.15   4
    11  0.028135025888  0.10  0.60  0.20  0.25  1.70  0.15   4
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275937   28
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     3 0.062422702335  0.10  0.20  0.20  0.40  2.70  0.40   0
    13  0.012834826008  0.10  0.60  0.20  0.25  1.70  0.15   0
     2 0.015267564803  0.10  0.40  0.20  0.45  2.70  0.15   1
     3 0.034014260230  0.10  0.20  0.20  0.40  2.70  0.40   1
     8 0.045541597247  0.10  0.20  0.20  0.40  2.70  0.40   1
     9 0.009691096222  0.10  0.20  0.20  0.40  2.70  0.40   1
    11  0.003278713311  0.10  0.60  0.20  0.25  1.70  0.15   1
     1 0.022534746277  0.10  0.40  0.20  0.45  1.70  0.15   2
     2 0.009947403482  0.10  0.40  0.20  0.45  2.70  0.15   2
     3 0.000149282269  0.10  0.20  0.20  0.40  2.70  0.40   2
     8 0.007745028877  0.10  0.20  0.20  0.40  2.70  0.40   2
     9 0.008896165588  0.10  0.20  0.20  0.40  2.70  0.40   2
    11  0.074523970418  0.10  0.60  0.20  0.25  1.70  0.15   2
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    19  0.007253338396  0.10  1.00  0.10  0.00  0.10  0.00   2
    21  0.010441945469  0.10  1.00  0.10  0.00  0.10  0.00   2
     1 0.016145290030  0.10  0.40  0.20  0.45  1.70  0.15   3
    11  0.102043182600  0.10  0.60  0.20  0.25  1.70  0.15   3
    13  0.007003252008  0.10  0.60  0.20  0.25  1.70  0.15   3
    19  0.169744402626  0.10  1.00  0.10  0.00  0.10  0.00   3
    22  0.000559932784  0.10  1.00  0.10  0.00  0.10  0.00   3
    11  0.022221526890  0.10  0.60  0.20  0.25  1.70  0.15   4
    19  0.208975721374  0.10  1.00  0.10  0.00  0.10  0.00   4
    22  0.019884895733  0.10  1.00  0.10  0.00  0.10  0.00   4
    11  0.000639759587  0.10  0.60  0.20  0.25  1.70  0.15   5
    19  0.083534245735  0.10  1.00  0.10  0.00  0.10  0.00   5
    22  0.021377084756  0.10  1.00  0.10  0.00  0.10  0.00   5
```

V:\data\projects\hydrology\vic_gen2\input\vegetation\docs\Figures\vpf_fraser_200_example.txt -- File date: 22/04/2016 -- File time: 12:03:22 PM

Elevation Band Parameter File

snb_fraser_200.txt -- Printed on 22/04/2016, 12:08:56 PM -- Page 1

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0    0    0    0
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277033 0.061103049310 0.668794883264 0.267878243264 0.002223824162 0.000000000000 0.000000000000
0.000000000000 0.000000000000 0.000000000000 0.000000000000 0.000000000000 0.000000000000 0.000000000000
0.000000000000 0.000000000000 0.000000000000  1194  1239  1468  1601    0    0    0    0    0    0    0    0    0
0    0    0
277034 0.456765790284 0.501035585773 0.042198623943 0.000000000000 0.000000000000 0.000000000000
0.000000000000 0.000000000000 0.000000000000 0.000000000000 0.000000000000 0.000000000000 0.000000000000
0.000000000000 0.000000000000 0.000000000000  1362  1476  1621    0    0    0    0    0    0    0    0    0    0
0    0    0
277035 0.485568659959 0.429977100563 0.063340726142 0.021113513336 0.000000000000 0.000000000000
0.000000000000 0.000000000000 0.000000000000 0.000000000000 0.000000000000 0.000000000000 0.000000000000
0.000000000000 0.000000000000 0.000000000000  1145  1248  1475  1674    0    0    0    0    0    0    0    0    0
0    0    0
277036 0.017766853684 0.457699647451 0.243345337946 0.197825790657 0.083362370261 0.000000000000
0.000000000000 0.000000000000 0.000000000000 0.000000000000 0.000000000000 0.000000000000 0.000000000000
0.000000000000 0.000000000000 0.000000000000  1188  1277  1494  1696  1853    0    0    0    0    0    0    0    0
0    0    0
278113 0.437813449322 0.208901252088 0.174416790061 0.136715941627 0.042152566902 0.000000000000
0.000000000000 0.000000000000 0.000000000000 0.000000000000 0.000000000000 0.000000000000 0.000000000000
0.000000000000 0.000000000000 0.000000000000  1107  1275  1505  1690  1830    0    0    0    0    0    0    0    0
```

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Vegetation Library File

vlbc_nalc_2005_final.txt -- Printed on 22/04/2016, 12:32:06 PM -- Page 1

```
#Class   OvrStry  Rarc  Rmin JAN-LAI  FEB-LAI  MAR-LAI  APR-LAI  MAY-LAI  JUN-LAI  JUL-LAI  AUG-LAI
SEP-LAI  OCT-LAI  NOV-LAI  DEC-LAI  JAN-ALB  FEB_ALB  MAR-ALB  APR-ALB  MAY-ALB  JUN-ALB  JUL-ALB
AUG-ALB  SEP-ALB  OCT-ALB  NOV-ALB  DEC-ALB  JAN-ROU  FEB-ROU  MAR-ROU  APR-ROU  MAY-ROU  JUN-ROU
JUL-ROU  AUG-ROU  SEP-ROU  OCT-ROU  NOV-ROU  DEC-ROU  JAN-DIS  FEB-DIS  MAR-DIS  APR-DIS  MAY-DIS
JUN-DIS  JUL-DIS  AUG-DIS  SEP-DIS  OCT-DIS  NOV-DIS  DEC-DIS  WIND_H   RGL  SolAtn     WndAtn
Trunk    COMMENT
1    1    50   182  1.00 1.00 1.00 1.10 1.25 1.41 1.56 1.26 1.17 1.07 1.00 1.00 0.11 0.11 0.10 0.10 0.09 0.09
0.09 0.09 0.10 0.10 0.11 0.11 2.16 2.16 2.16 2.05 1.97 1.91 1.85 1.97 2.01 2.06 2.16 2.16 9.01 9.01 9.01 9.18
9.42 9.63 9.82 9.43 9.29 9.13 9.01 9.01 30   30   0.88 1.97 0.3  Temperate or sub-polar needleleaf forest -
sub-alpine/sub-polar/open
2    1    50   182  1.80 1.80 1.80 1.90 2.00 2.15 2.36 2.00 1.90 1.80 1.80 1.80 0.10 0.09 0.09 0.08 0.08 0.08
0.08 0.08 0.09 0.09 0.09 0.10 1.99 1.99 1.99 1.96 1.92 1.88 1.82 1.92 1.96 1.99 1.99 1.99 11.36     11.36
11.36     11.47     11.59     11.74     11.95     11.59     11.47     11.36     11.36     11.36     30   30
0.88 2.30 0.3  Temperate or sub-polar needleleaf forest - high-elevation
3    1    50   182  2.50 2.50 2.50 2.75 3.00 3.28 3.28 3.00 2.75 2.50 2.50 2.50 0.09 0.09 0.08 0.08 0.08 0.08
0.08 0.08 0.08 0.09 0.09 0.10 2.27 2.27 2.27 2.19 2.11 2.03 2.03 2.11 2.19 2.27 2.27 2.27 15.44     15.44
15.44     15.72     15.97     16.24     16.23     15.97     15.72     15.44     15.44     15.44     30   30
0.88 2.62 0.3  Temperate or sub-polar needleleaf forest - mid-elevation
4    1    50   182  3.18 3.18 3.18 3.46 3.74 4.17 4.07 3.45 3.32 3.18 3.18 3.18 0.09 0.09 0.08 0.08 0.08 0.08
0.08 0.08 0.08 0.09 0.09 0.10 2.59 2.59 2.59 2.50 2.41 2.28 2.31 2.50 2.55 2.59 2.59 2.59 20.36     20.36
20.36     20.68     20.98     21.40     21.30     20.67     20.52     20.36     20.36     20.36     40   30
0.88 2.89 0.3  Temperate or sub-polar needleleaf forest - coastal/humid/dense
5    1    50   182  0.72 0.72 0.72 0.79 0.85 0.94 1.00 1.00 0.96 0.88 0.76 0.72 0.12 0.12 0.12 0.11 0.11 0.11
0.10 0.10 0.11 0.11 0.12 0.12 1.26 1.26 1.26 1.32 1.37 1.44 1.49 1.48 1.46 1.40 1.30 1.26 5.81 5.81 5.81 5.91
6.00 6.12 6.20 6.19 6.15 6.05 5.88 5.81 20   30   0.88 1.68 0.3  Sub-polar taiga needleleaf forest
6    1    25   172  4.32 4.32 4.32 4.65 4.98 5.38 5.38 4.98 4.65 4.32 4.32 4.32 0.16 0.15 0.14 0.14 0.14 0.14
0.14 0.14 0.14 0.15 0.16 0.16 2.01 2.01 2.01 1.93 1.86 1.77 1.77 1.86 1.93 2.01 2.01 2.01 19.31     19.31
19.31     19.56     19.81     20.09     20.09     19.81     19.57     19.31     19.31     19.31     40   30
0.79 3.36 0.3  Tropical or sub-tropical broadleaf evergreen
7    1    40   172  4.32 4.32 4.32 4.65 4.98 5.38 5.38 4.98 4.65 4.32 4.32 4.32 0.16 0.15 0.14 0.14 0.14 0.14
0.14 0.14 0.14 0.15 0.16 0.16 1.24 1.24 1.24 1.19 1.14 1.09 1.09 1.14 1.19 1.24 1.24 1.24 11.88     11.88
11.88     12.04     12.19     12.36     12.36     12.19     12.04     11.88     11.88     11.88     40   30
0.78 1.35 0.6  Tropical or sub-tropical broadleaf deciduous
8    1    40   169  0.20 0.20 0.20 0.22 0.52 1.57 2.03 1.47 0.40 0.23 0.20 0.20 0.19 0.19 0.19 0.17 0.15 0.14
0.14 0.14 0.16 0.17 0.19 0.19 0.97 0.97 0.97 1.03 1.56 1.85 1.70 1.89 1.36 1.03 0.97 0.97 6.51 6.51 6.51 6.66
7.91 9.84 10.33     9.71 7.49 6.68 6.51 6.51 30   30   0.78 1.35 0.6  Temperate or sub-polar broadleaf deciduous
9    1    45   217  0.86 0.86 0.86 1.12 1.38 2.49 2.81 2.03 1.50 0.96 0.86 0.86 0.13 0.13 0.13 0.12 0.11 0.10
0.10 0.10 0.11 0.12 0.13 0.13 1.88 1.88 1.88 1.91 1.80 1.48 1.41 1.59 1.76 1.98 1.88 1.88 8.20 8.20 8.20 8.64
9.00 10.06     10.29     9.69 9.14 8.38 8.20 8.20 30   30   0.85 2.08 0.45  Mixed Forest
10   0    2.5  172  0.25 0.25 0.25 0.50 0.90 1.13 1.17 1.04 0.74 0.25 0.25 0.25 0.19 0.19 0.18 0.17 0.15 0.15
0.15 0.15 0.16 0.19 0.19 0.19 0.14 0.14 0.14 0.20 0.26 0.25 0.25 0.26 0.24 0.14 0.14 0.14 0.85 0.85 0.85 0.98
1.10 1.15 1.16 1.14 1.06 0.85 0.85 0.85 10   30   0.79 0    0    Tropical or sub-tropical shrubland
11   0    2.5  169  0.25 0.25 0.25 0.50 0.90 1.13 1.17 1.04 0.74 0.25 0.25 0.25 0.19 0.19 0.18 0.17 0.15 0.15
0.15 0.15 0.16 0.19 0.19 0.19 0.14 0.14 0.14 0.20 0.26 0.25 0.25 0.26 0.24 0.14 0.14 0.14 0.85 0.85 0.85 0.98
1.10 1.15 1.16 1.14 1.06 0.85 0.85 0.85 10   30   0.79 0    0    Temperate or sub-polar shrubland
12   0    2    175  0.28 0.28 0.28 0.46 0.65 0.86 0.84 0.60 0.33 0.33 0.28 0.28 0.21 0.20 0.20 0.19 0.18 0.18
0.18 0.19 0.20 0.20 0.21 0.21 0.08 0.08 0.08 0.10 0.12 0.13 0.13 0.11 0.09 0.09 0.08 0.08 0.44 0.44 0.44 0.48
0.52 0.55 0.54 0.51 0.45 0.45 0.44 0.44 10   30   0.75 0    0    Tropical or sub-tropical grassland
13   0    2    130  0.28 0.28 0.28 0.46 0.65 0.86 0.84 0.60 0.33 0.33 0.28 0.28 0.21 0.20 0.20 0.19 0.18 0.18
0.18 0.19 0.20 0.20 0.21 0.21 0.08 0.08 0.08 0.10 0.12 0.13 0.13 0.11 0.09 0.09 0.08 0.08 0.44 0.44 0.44 0.48
0.52 0.55 0.54 0.51 0.45 0.45 0.44 0.44 10   30   0.75 0    0    Temperate or sub-polar grassland
14   0    2.5  169  0.47 0.47 0.47 0.69 0.91 1.20 1.32 1.29 1.11 0.76 0.47 0.47 0.18 0.17 0.17 0.16 0.15 0.15
0.14 0.15 0.15 0.16 0.18 0.18 0.10 0.10 0.10 0.12 0.14 0.13 0.12 0.12 0.13 0.13 0.10 0.10 0.48 0.48 0.48 0.52
0.55 0.58 0.59 0.59 0.57 0.53 0.48 0.48 10   30   0.79 0    0    Sub-polar or polar shrubland-lichen-moss
15   0    10   161  0.40 0.40 0.40 0.46 0.52 0.74 0.88 0.76 0.61 0.50 0.40 0.40 0.21 0.20 0.20 0.19 0.19 0.18
0.18 0.18 0.19 0.20 0.20 0.21 0.03 0.03 0.03 0.03 0.03 0.04 0.04 0.04 0.04 0.03 0.03 0.03 0.12 0.12 0.12 0.12
0.12 0.13 0.14 0.13 0.13 0.12 0.12 0.12 10   30   0.75 0    0    Sub-polar or polar grassland-lichen-moss
16   0    10   161  0.40 0.40 0.40 0.40 0.40 0.40 0.40 0.40 0.40 0.40 0.40 0.40 0.21 0.20 0.20 0.19 0.19 0.19
0.19 0.19 0.19 0.20 0.20 0.21 0.02 0.02 0.02 0.02 0.02 0.02 0.02 0.02 0.02 0.02 0.02 0.02 0.05 0.05 0.05 0.05
0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05 10   30   0.75 0    0    Sub-polar or polar barren-lichen-moss
17   0    3    100  0.69 0.69 0.69 0.83 1.31 1.59 1.67 1.55 1.22 0.96 0.69 0.69 0.17 0.17 0.16 0.16 0.14 0.14
0.14 0.14 0.15 0.16 0.17 0.17 0.23 0.23 0.23 0.25 0.24 0.23 0.23 0.23 0.25 0.27 0.23 0.23 1.05 1.05 1.05 1.09
1.19 1.23 1.24 1.23 1.17 1.12 1.05 1.05 10   30   0.79 0    0    Wetland
18   0    2    93   0.00 0.10 0.20 0.22 0.52 1.57 2.03 1.47 0.40 0.23 0.11 0.00 0.21 0.21 0.20 0.20 0.19 0.18
0.18 0.18 0.19 0.20 0.21 0.21 0.01 0.01 0.02 0.02 0.03 0.09 0.11 0.09 0.03 0.02 0.01 0.01 0.08 0.08 0.08 0.08
0.13 0.48 0.65 0.44 0.09 0.08 0.08 0.08 10   30   0.75 0    0    Cropland
19   0    9999 9999 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.21 0.21 0.21 0.21 0.21 0.21
```

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0.21 0.21 0.21 0.21 0.21 0.21 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.08 0.08 0.08 0.08
0.08 0.08 0.08 0.08 0.08 0.08 0.08 0.08 10   9999 0    0    0    Barren Lands
20   1    31   217  0.76 0.76 0.84 1.45 1.85 2.05 2.04 1.82 1.39 1.08 0.76 0.76 0.13 0.13 0.13 0.11 0.10 0.10
0.10 0.10 0.11 0.12 0.13 0.14 1.30 1.30 1.36 1.30 1.21 1.17 1.17 1.21 1.32 1.41 1.30 1.30 5.87 5.87 5.99 6.66
6.98 7.11 7.10 6.95 6.61 6.29 5.87 5.87 20   30   0.85 2.04 0.45 Urban and Built-up
21   0    9999 9999 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.07 0.07 0.07 0.07 0.07 0.07
0.07 0.07 0.07 0.07 0.07 0.07 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.04 0.04 0.04 0.04
0.04 0.04 0.04 0.04 0.04 0.04 0.04 0.04 10   9999 0    0    0    Water
22   0    9999 9999 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.65 0.65 0.65 0.65 0.65 0.65
0.65 0.65 0.65 0.65 0.65 0.65 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.04 0.04 0.04 0.04
0.04 0.04 0.04 0.04 0.04 0.04 0.04 0.04 10   9999 0    0    0    Snow and Ice
```