

# **ALGORITHMS for LAND SURFACE CHARACTERISTICS in the HIGH-RESOLUTION EXTERNAL LAND SURFACE MODELING SYSTEM GEM-Surf**

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## **INTRODUCTION**

### **Objective**

Generate all the land surface fields for the high-resolution GEM-Surf to be tested over Canada, with grid spacing of 200m for the entire country. These fields will be generated for urban and non-urban portions of the land surface.

### **Available datasets**

Land Cover Circa-2000 (LCC-2000): Information on land use / land cover (LULC) for Canada, resolution of 1:50,000 (about 30m), obtained from the Geobase web site.

10-year climatology for the Normalized Difference Vegetation Index (NDVI) from the Moderate Resolution Imaging Spectroradiometer (MODIS), global, 1km, obtained from Rajat Bindlish at the United States Department of Agriculture (USDA).

8-year evolution of leaf area index (*LAI*) over North America (10-km grid spacing) obtained from an integration of the Biome-BGC terrestrial ecosystem model, obtained from Douglas Chan and Misa Ishizawa from the Climate Research Division (Downsview).

10-year climatology (2000-2009) of the Moderate Resolution Imaging Spectroradiometer (MODIS) bidirectional reflectance distribution function (BRDF) albedo snow-free 16-day products.

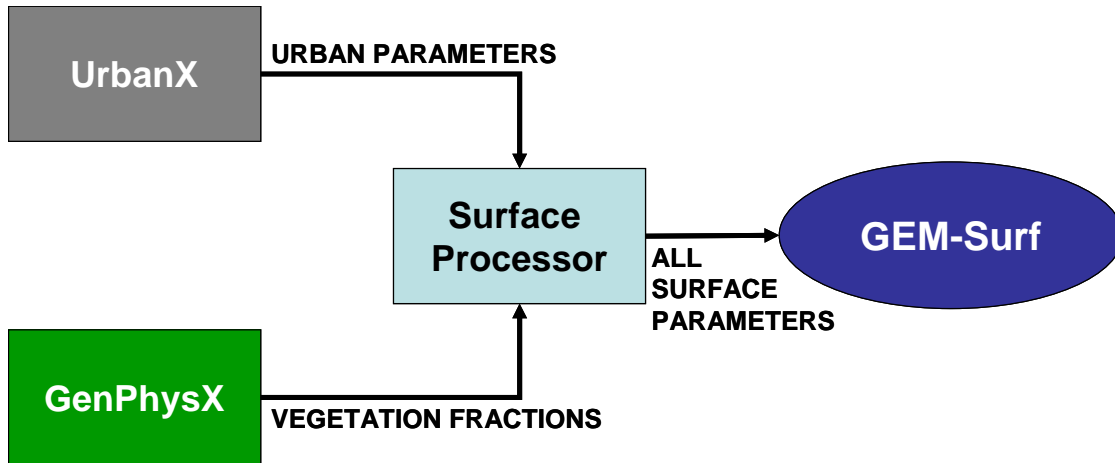
CanVec database, a digital cartographic reference product generated by Natural Resources Canada (NRC). This database offers quality topographic information in vector format, including information on cities.

Canadian census data, from 2006, which provide statistical information about the population, households, dwellings, and families.

Digital models of three-dimensional building (generally in 2.5D, i.e., x, y, with information on the height of specific buildings).

## GENERAL STRATEGY

The following diagram describes the strategy that is used to produce all the land surface fields (parameters) necessary to run the external land surface modeling system (GEM-Surf).



In this figure, GenPhysX is a tool that was developed at MSC to specify surface characteristics over natural (non-urban) land areas directly on the GEM-Surf grid. GenPhysX produces the RPN standard file containing the geophysical fields normally used to run the GEM atmospheric model: VF (fractional coverage for each land cover type), MG (land fractional coverage), ME (filtered orography), etc., as well as a second file that will be read by the pre-processor to get SSS (small-scale standard deviation for orography), which is essential to compute the orographic component of the roughness length.

UrbanX, on the other hand, is a module that provides all the urban parameters over cities using inputs from the CanVec database, the Canadian census data, digital models of three-dimensional buildings (when available), and the Land Cover Circa 2000. This software is run on smaller domains (typically similar to a medium-size city) included into the larger GEM-Surf grid. At this moment, the maximum size of the UrbanX grid must be smaller than about 45km X 45km so that several UrbanX grids (domains) have to be used to cover the GEM-Surf grid. These sub-domains can also cover only a part of the background grid. The UrbanX grid points and the background grid points have to superimposed exactly.

The “Surface Processor” gathers information from both UrbanX and GenPhysX and, in the process of generating all the surface parameters required by GEM-Surf, ensures that all these fields are consistent.

## URBAN PARAMETERS

The list of urban parameters produced by UrbanX is the following:

<b>STD etiket</b>	<b>Full name</b>
NATF	fraction of natural surface
BLDF	fraction of building
PAVF	fraction of paved area
BLDH	Building height
ZORF	Roof aerodynamic roughness length
ZORD	Road aerodynamic roughness length
ALRF	albedo roof
ALRD	albedo road
ALWL	albedo wall
EMRF	emissivity roof
EMRD	emissivity road
EMWL	emissivity wall
HCRF	(ip1=1199) heat capacity layer 1 roof
HCRD	(ip1=1199) heat capacity layer 1 road
HCWL	(ip1=1199) heat capacity layer 1 wall
HCRF	(ip1=1198) heat capacity layer 2 roof
HCRD	(ip1=1198) heat capacity layer 2 road
HCWL	(ip1=1198) heat capacity layer 2 wall
HCRF	(ip1=1197) heat capacity layer 3 roof
HCRD	(ip1=1198) heat capacity layer 3 road
HCWL	(ip1=1197) heat capacity layer 3 wall
TCRF	(ip1=1199) thermal conductivity layer 1 roof
TCRD	(ip1=1199) thermal conductivity layer 1 road
TCWL	(ip1=1199) thermal conductivity layer 1 wall
TCRF	(ip1=1198) thermal conductivity layer 2 roof
TCRD	(ip1=1198) thermal conductivity layer 2 road
TCWL	(ip1=1198) thermal conductivity layer 2 wall
TCRF	(ip1=1197) thermal conductivity layer 3 roof
TCRD	(ip1=1197) thermal conductivity layer 3 road

TCWL	(ip1=1197) thermal conductivity layer 3 wall
DPRF	(ip1=1199) heat capacity layer 1 roof
DPRD	(ip1=1199) heat capacity layer 1 road
DPWL	(ip1=1199) thickness layer 1 wall
DPRF	(ip1=1198) thickness layer 2 roof
DPRD	(ip1=1198) thickness layer 2 road
DPWL	(ip1=1198) thickness layer 2 wall
DPRF	(ip1=1197) thickness layer 3 roof
DPRD	(ip1=1197) thickness layer 3 road
DPWL	(ip1=1197) thickness layer 3 wall
QHTR	sensible anthropogenic heat flux generated by traffic road
QETR	Latent anthropogenic heat flux generated by traffic road
QHIN	sensible anthropogenic heat flux generated by industry roof
QEIN	latent anthropogenic heat flux generated by industry roof
WHOR	S_wall/S_horizontal canopy
Z0TW	Canopy aerodynamic roughness length canopy

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## LAND SURFACE PARAMETERS (NON-URBAN)

The land surface variables to initialize for GEM-Surf are the following:

- $z_{0m}$ : total roughness length for momentum turbulent transfers, including orographic, vegetation, and urban components, representative of an area larger than the model grid area (m)
- $z_{0m\_local}$ : roughness length for momentum turbulent transfers, including only the vegetation and urban (local) components, and representative of the model grid area (m).
- $veg_{low}$ : fractional coverage of low vegetation (grass, crops, shrubs) over land,
- $veg_{high}$ : fractional coverage of high vegetation (forests) over land,
- $veg$ : total fractional coverage of vegetation over land,
- $LAI$ : total leaf area index over vegetation area of the land surface ( $m^2 m^{-2}$ ),
- $LAI_{vh}$ : leaf area index over high-vegetation area of the land surface ( $m^2 m^{-2}$ ),
- $sand$ : sand fraction of soil (%),
- $clay$ : clay fraction of soil (%),
- $d_{rz}$ : root-zone depth (m),
- $D_d$ : drainage density ( $m^{-1}$ ),
- $R_{smin}$ : minimum stomatal resistance ( $s m^{-1}$ ),
- $\gamma, R_{gl}$ : vegetation parameters for the calculation of the stomatal resistance,
- $B$ : form parameter for subgrid-scale surface flow (or runoff),
- $\alpha_{g\_WS}$ : bare ground broadband white-sky (diffused radiation) snow-free albedo for visible and near-infrared,
- $\alpha_{g\_BS}$ : bare ground broadband black-sky (direct radiation) snow-free albedo for visible and near-infrared,
- $\alpha_{veg\_WS}$ : vegetation broadband white-sky (diffused radiation) snow-free albedo for visible and near-infrared,
- $\alpha_{veg\_BS}$ : vegetation broadband black-sky (direct radiation) snow-free albedo for visible and near-infrared,
- $\varepsilon$ : emissivity of the non-urban land surface,
- $\varepsilon_v$ : emissivity of vegetation, and
- $\varepsilon_{bare}$ : emissivity of bare soil.

## VEGETATION FRACTIONAL COVERAGES from GenPhysX and UrbanX

In the above diagram, the GenPhysX and UrbanX modules are integrated in parallel, both generating fractional coverages for each type of vegetation that may not be consistent. For instance, GenPhysX does not consider the detailed information that is available in UrbanX for cities, and it is thus expected that the VFs generated by each software will differ.

Consistency for the vegetation fractional coverages are obtained this way:

```
IF      PAVF + BLDF =  $VF_U(21)$  > threshold THEN
      VFs are specified using UrbanX values,
ELSE
      VFs are specified using redistributed GenPhysX values over the unbuilt area as
      viewed by UrbanX, following:
      - for all  $kk$  except 21
          
$$VF(kk) = \frac{VF_G(kk)}{(1 - VF_G(21))} (1 - PAVF - BLDF)$$

      where  $VF_G(kk)$  is from GenphysX
END IF
```

This procedure respects the following requirement:

$$\sum_{all\ kk\ except\ 21} VF(kk) + PAVF + BLDF = 1$$

## VEGETATION FRACTION

The three fractions for vegetation coverages are mostly determined by the LCC-2000 land use / land cover database, as aggregated on the target GEM-Surf grid. Based on the RPN classification for vegetation, with  $kk$  indicated in the first column:

- 1 (salt) water
- 2 ice
- 3 inland lake
- 4 evergreen needleleaf trees
- 5 evergreen broadleaf trees
- 6 deciduous needleleaf trees
- 7 deciduous broadleaf trees
- 8 tropical broadleaf trees
- 9 drought deciduous trees
- 10 evergreen broadleaf shrub
- 11 deciduous shrubs
- 12 thorn shrubs
- 13 short grass and forbs
- 14 long grass
- 15 crops
- 16 rice
- 17 sugar
- 18 maize
- 19 cotton
- 20 irrigated crops
- 21 urban
- 22 tundra
- 23 swamp
- 24 desert
- 25 mixed wood forests
- 26 mixed shrubs

The fractional coverage for high vegetation is given by:

$$veg_{high} = \frac{\sum_{kk=4-9,25,26} VF_{kk} veg_{kk}}{\sum_{kk=4-20,22-26} VF_{kk}} .$$

(note, a value of  $veg_{high} = 0.9$  could also simply be used)

The look-up table for  $veg_{kk}$  is provided in GEM's subroutine "inicover.ftn". In the equation above,  $veg_{high}$  is constant throughout the year.

For low vegetation, the fractional coverage changes during the year, in relation with crops phenology, and is given by:

$$veg_{low} = \frac{\sum_{kk=10-14,22-24} VF_{kk} veg_{kk} + \sum_{kk=15-20} VF_{kk} veg_{crops}}{\sum_{kk=4-20,22-26} VF_{kk}}$$

where  $veg_{crops}$  is associated with LAI (and NDVI), and is described in a section below. The total fractional coverage for vegetation is simply:

$$veg = veg_{low} + veg_{high}$$

It should be noted that LULC classifications other than the one above (labeled “RPN”) could be used for this.

## LEAF AREA INDEX

### Overview of LAI algorithm

The specification of LAI on the high-resolution GEM-Surf grids is done in two steps. First, climatological LAI obtained from the Biome-BGC ecosystem terrestrial model is downscaled from its 10-km grid to a 1-km grid, based on information from the MODIS 1-km NDVI climatology and from the LCC-2000 database. To achieve this, a climatology of the Biome-BGC has been produced (based on 8 years of outputs provided by Douglas and Misa). The second step is to downscale the LAI-1km (from the previous step) to the target grid (200m or 500m) using LULC information from LCC-2000. For this last part, the VF fields have to be computed on the target grid using GenPhysX.

### LAI downscaling to 1km NDVI grid

#### a) *Climatology of Biome-BGC LAI*

The Biome-BGC LAI outputs can be obtained at this location:  
schuetz:/users/dor/armn/gry/local/lai\_ecotype

The files have names of the style “eco\_{\$type}{\$year}.fst”, where \$year is the year of the results (between 2002 and 2010), and \$type is for the type of vegetation: “c3g” is for c3 grass, “c4g” is for c4 grass, “dbf” is for deciduous broadleaf forest, “dsh” is for deciduous shrub, “ebf” is for evergreen broadleaf forest, “enf” is for evergreen needleleaf forest, and “esh” is for evergreen shrub.

For each of these types, a climatology has been constructed, with one value of LAI every 10 days (no need here to average, just using the values in the middle of the period is

sufficient). So we get 36 LAI fields for each type, which can be used to evaluate  $LAI_{min}(k)$  and  $LAI_{max}(k)$  on the native 10-km grid.

#### b) *Minimum and maximum NDVI*

The climatology of the NDVI has already been built by our colleagues at USDA. Here, only need to find the minimum and maximum during the year:  $NDVI_{min}$  and  $NDVI_{max}$ , on the 1-km native grid of the NDVI products.

These files can be found at:

Poseidon:/local/data/afsmvan/GIS/VI\_Climatology/NDVI

#### c) *Downscaling of LAI to the 1-km grid*

This is simply done using:

$$\underbrace{LAI_{1km}(k)}_{1km} = \underbrace{LAI_{min}(k)}_{10km} + \underbrace{\left( \frac{NDVI - NDVI_{min}}{NDVI_{max} - NDVI_{min}} \right)}_{1km} \underbrace{[LAI_{max}(k) - LAI_{min}(k)]}_{10km}$$

in which  $LAI_{1km}(k)$  is the downscaled LAI for type  $k$ , and  $NDVI$  is the value for the specific 10-day period.

These files can be found at:

Poseidon:/local/data/afsmvan/GIS/LAI/LAI\_1km

### **LAI downscaling to the GEM-Surf target grid**

#### a) *Vegetation fractions on the 1-km grid*

In order to perform the downscaling of the LAI to the GEM-Surf high-resolution grids (200m or 500m), it is first required to compute the fractional coverage of each type of vegetation at this scale. For this, GenPhysX has to be run to produce the  $VF'(kk)$  fields on GEM-Surf's target grid, and using the LCC-2000 database (same as described above for the fractional vegetation coverages  $veg_{low}$  and  $veg_{high}$ ). Here,  $kk$  refers to the index of the RPN land use / land cover classification (given above, with  $kk$  in the first column).

Then, a conversion is required to remap these fractions onto the classification that was used to generate the LAI with the Biome-BGC model:

$$VF(cg) = VF'(13) + VF'(14) + VF'(15) + VF'(16) + VF'(17) + VF'(18) \\ + VF'(19) + VF'(20) + VF'(22)$$

$$VF(dbf) = VF'(7) + VF'(9) + 0.5 VF'(25)$$

$$VF(dsh) = VF'(11) + 0.5 VF'(26)$$

$$VF(ebf) = VF'(5) + VF'(8)$$

$$VF(enf) = VF'(4) + 0.5 VF'(25)$$

$$VF(esh) = VF'(10) + VF'(12) + 0.5 VF'(26)$$

where cg stands for grass (both of type 3 and 4). Note the  $VF'(6)$  does not appear (does not exist in the database...),  $VF'(23)$  for swamps does not appear either, and  $VF'(21)$  is for urban areas.

b) *Downscaling to the target grid (200m or 500m)*

This is done using:

$$LAI_{target} = \frac{\sum VF(k) LAI_{1km}(k)}{\sum VF(k)}$$

for the LAI associated with the vegetation part of the model grid area (i.e., what is needed for GEM and GEM-Surf), and

$$LAI_{target}^* = \sum VF(k) LAI_{1km}(k)$$

for the grid-scale LAI (i.e., what is need to compare with satellite estimates). It should be noted that for grass,

$$LAI(k = cg) = \max[LAI(cg3), LAI(cg4)]$$

These results can be found at:

Poseidon:/local/data/afsmvan/GIS/LAI/Target

It should be noted that another LAI has to be calculated for the new MISBA land surface scheme, for the high-vegetation portion of the canopy. This is obtained using:

$$LAI_{vh} = \frac{\sum_{k=4-9; 25-26} VF(k) LAI_{1km}(k)}{\sum_{k=4-9, 25-26} VF(k)}$$

## **Crops (vegetation) fractional coverage**

In a manner similar to what is done for LAI, the fractional coverage for the portion of the model grid area covered by crops can be written as:

$$veg_{crops} = \min \left[ 0.90, \left( \frac{NDVI - NDVI_{\min}}{NDVI_{\max} - NDVI_{\min}} \right)^{1/2} \right],$$

calculated on the target grid.

These results can be found at:

Poseidon:/local/data/afsmvan/GEM-Surf/Fract-Cover/

## **SURFACE ALBEDOS**

The surface albedos for white sky (diffuse) and black sky (direct) radiation have to be specified for both the “ground” and “vegetation” segments of the model grid area. This is done using LULC information at the target grid scale, i.e., the  $VF(kk)$  fractions described above, the LAI and fractional vegetation coverage fractions produced on GEM-Surf’s target grid (as described above), and a 10-year climatology of MODIS BRDF snow-free albedo 16-day products (MCD43C2). This MODIS climatology is provided on a global 5-km grid, and consists of parameters used in the BRDF RossThickLiSparseReciprocal model, i.e.,  $f_{iso}$ ,  $f_{vol}$ , and  $f_{geo}$ , for both the shortwave band, including visible and near-infrared radiation bands.

Based on this approach, the black-sky albedo is:

$$\alpha_{bs}(\theta) = f_{iso} [g_{0iso} + g_{1iso}\theta^2 + g_{2iso}\theta^3] + f_{vol} [g_{0vol} + g_{1vol}\theta^2 + g_{2vol}\theta^3] + f_{geo} [g_{0geo} + g_{1geo}\theta^2 + g_{2geo}\theta^3]$$

where  $\theta$  is the solar angle, and the “g” parameters are given by:

	<b>Isotropic (iso)</b>	<b>RossThick (vol)</b>	<b>LiSparseR (geo)</b>
g0	1.0	-0.007574	-1.284909
g1	0.0	-0.070987	-0.166314
g2	0.0	0.307588	0.041840

The white-sky albedo is given by:

$$\alpha_{ws} = f_{iso}g_{iso} + f_{vol}g_{vol} + f_{geo}g_{geo} \quad ,$$

with  $g_{iso} = 1.0$ ,  $g_{vol} = 0.189184$ , and  $g_{geo} = 1.377622$ .

The general procedure to specify the white-sky and black-sky albedos for the GEM-Surf integration grid (the target grid), is the following:

- A. Fill gaps in the MODIS climatology for northern regions during the cold season (missing values in the MODIS retrievals due to the presence of snow).
- B. For each 10-day period of the year, calculate climatological values of shortwave white-sky and black-sky albedos on the 5-km global domain using a single solar angle (i.e., not evolving during the day) chosen such that it best represents the total absorbed energy at the surface;
- C. Downscale to high-resolution target grid to obtain the land surface albedos that will be used by ISBA in GEM-Surf.
- D. Disaggregate the downscaled albedos into components representative of vegetation and bare soil, to be used by MISBA in GEM-Surf.

**A.** The parameters estimated from MODIS to calculate the black-sky and white-sky albedos are representative of the land surface component of the Earth, and do not include the effect of water surfaces. Therefore, for most of the Earth's surface, these albedos can be directly used to initialize the GEM model including the ISBA land surface scheme (for MISBA, a disaggregation into albedos for vegetation and for bare soil is necessary).

One problem, however, is related to the absence of albedo values over northern regions in the cold season, a characteristic of the MODIS snow-free retrieval algorithms (related to the presence of snow). Before proceeding with the calculation of the black-sky and white-sky albedos, it is thus necessary to fill the missing values. This is done by temporally interpolating the  $f_{iso}$ ,  $f_{vol}$ , and  $f_{geo}$  parameters described above, for the points and time with missing values.

**B.** For several reasons, related with simplicity's sake and uncertainties associated with the disaggregation process required to specify the ground and vegetation components of the surface albedos, only broadband white-sky and black-sky albedos are used in the land surface modeling system for the shortwave portion of the electromagnetic spectrum. This is obtained from the equations above using an angle that approximates as much as possible the total absorbed solar energy at the surface.

This total absorbed energy is given by:

$$SW_{tot} = 2 \int_{\pi/2}^{\theta_z} SW_{BS} (1 - \alpha_{BS}) d\theta + 2 \int_{\pi/2}^{\theta_z} SW_{WS} (1 - \alpha_{WS}) d\theta$$

where  $\theta_z$  is the solar angle at zenith, whereas  $SW_{BS}$  and  $SW_{WS}$  are the clear-sky and white-sky incident shortwave radiation fluxes at the surface. The main assumption to get a mean black-sky albedo  $\overline{\alpha_{BS}}$  is the following:

$$SW_{tot} \approx 2 \int_{\pi/2}^{\theta_z} SW_{BS} \left(1 - \overline{\alpha_{BS}}\right) d\theta + 2 \int_{\pi/2}^{\theta_z} SW_{WS} (1 - \alpha_{WS}) d\theta$$

Using the two previous equations, we get:

$$\int_{\pi/2}^{\theta_z} SW_{BS} \left(1 - \overline{\alpha_{BS}}\right) d\theta = \int_{\pi/2}^{\theta_z} SW_{BS} (1 - \alpha_{BS}) d\theta$$

which can be rewritten as:

$$\overline{\alpha_{BS}} = 1 - \frac{\int_{\pi/2}^{\theta_z} SW_{BS} (1 - \alpha_{BS}) d\theta}{\int_{\pi/2}^{\theta_z} SW_{BS} d\theta}$$

$$\Leftrightarrow \overline{\alpha_{BS}} = \frac{\int_{\pi/2}^{\theta_z} SW_{BS} \alpha_{BS} d\theta}{\int_{\pi/2}^{\theta_z} SW_{BS} d\theta}$$

An approximate solution to this equation can be obtained by numerical integration and by supposing an sinusoidal evolution of the downward solar radiation, following:

$$SW_{BS} = SW_{BSmax} \sin \left[ \frac{\pi}{2} \frac{(\pi/2 - \theta)}{(\pi/2 - \theta_z)} \right]$$

where  $SW_{BSmax}$  is the maximum incident direct solar radiation at zenith. Using this in the preceding equation, we get, as a numerical solution:

$$\overline{\alpha_{BS}} = \frac{\sum_{\pi/2 \rightarrow \theta_z} \sin \left[ \frac{\pi}{2} \frac{(\pi/2 - \theta)}{(\pi/2 - \theta_z)} \right] \alpha_{BS}(\theta) \Delta\theta}{\sum_{\pi/2 \rightarrow \theta_z} \sin \left[ \frac{\pi}{2} \frac{(\pi/2 - \theta)}{(\pi/2 - \theta_z)} \right] \Delta\theta}$$

in which  $\Delta\theta$  are the increments for the numerical integration.

C. The downscaling of  $\overline{\alpha_{BS}}$  and  $\overline{\alpha_{WS}}$  is done in a very simple manner, i.e., by interpolation to the GEM-Surf target grid.

D. In order to disaggregate both of the broadband albedos into ground and vegetation components, the snow-free albedos downscaled to GEM-Surf target grid can be written in this manner:

$$\alpha_{\psi,200m} = (1 - veg - f_{urb})\alpha_{\psi,bare} + veg \alpha_{\psi,veg} + f_{urb} \alpha_{\psi,urb}$$

in which  $\psi$  stands for either for white-sky or black-sky radiation,  $veg$  is the vegetation fractional coverage over land (described and calculated in a previous subsection),  $f_{urb}$  is the fractional coverage over land of urban areas (roads and buildings), and  $\alpha_{\psi,bare}$ ,  $\alpha_{\psi,veg}$ ,  $\alpha_{\psi,urb}$  are the ground, vegetation, and urban albedos (for either direct and diffuse radiation).

In the event that a larger fraction of land is covered by vegetation ( $veg > 0.10$ ), the ground albedos for both direct and diffuse radiation are first calculated based on the sand and clay fraction in the soil, as well as wetness of the soil (if available). A bi-linear approach is used to interpolate between the albedo values of four “extreme” soil types: dry-sand, wet-sand, dry-clay and wet-clay. These values are listed in the Table below.

**Table.** Albedo and emissivity values for soil types based on *Handbook of Soil Science, M.E. Summer, 2000.*

Soil Type	Albedo	Emissivity
dry sand	0.35 ( $\alpha_{drysand}$ )	0.95 ( $\epsilon_{drysand}$ )
wet sand	0.24 ( $\alpha_{wetsand}$ )	0.98 ( $\epsilon_{wetsand}$ )
dry clay	0.15 ( $\alpha_{dryclay}$ )	0.95 ( $\epsilon_{dryclay}$ )
wet clay	0.08 ( $\alpha_{wetclay}$ )	0.97 ( $\epsilon_{wetclay}$ )

The bare ground albedos are thus:

$$\alpha_{\psi,bare} = \alpha_{drysand} A(1 - SWI) + \alpha_{dryclay} (1 - A)(1 - SWI) + \alpha_{wetsand} A SWI + \alpha_{wetclay} (1 - A) SWI$$

in which  $A = sand / (sand + clay)$  and  $SWI = (w_{1cm} - w_{wilt}) / (w_{sat} - w_{wilt})$  is the so-called soil wetness index, where  $w_{1cm}$  is the soil moisture content for the 1-cm near-surface layer and  $w_{wilt}$  is the soil water content at the wilting point. It should be noted that the superficial soil layer can dry past the wilting point or become supersaturated, but  $SWI$  must be constrained to the [0,1] range ( $A$  is in this range by construction). If soil moisture is not available, then a value of  $SWI = 0.5$  can be used. Note also that the bare soil albedos are considered to be the same for diffuse and direct radiation.

The albedos for the urban areas are simply specified from the roads, walls, and roofs albedos:

$$\alpha_{\psi,urb} = \frac{\alpha_{road} + \alpha_{wall} + \alpha_{roof}}{3}$$

whereas the fraction  $f_{urb} = f_{pav} + f_{bld}$  (fractions of pavement and of building).

The albedos for the vegetation part of the grid are obtained from:

$$\alpha_{\psi,veg} = \frac{\alpha_{\psi,200m} - (1 - veg - f_{urb})\alpha_{\psi,bare} - f_{urb}\alpha_{\psi,urb}}{(veg)}$$

For the other situation in which a larger portion of land is covered by bare ground ( $veg < 0.1$ ), then the vegetation albedoes are first specified following:

$$\alpha_{\psi,veg} = \frac{\sum_{kk=4-20; 22-23, 25-26} VF(kk) \alpha_{\psi,vegLU}(kk)}{\sum_{kk=4-20; 22-23, 25-26} VF(kk)}$$

where  $\alpha_{vegLU,\psi}(kk)$  is obtained from the look-up table provided at the end of this document (from Houldcroft et al. 2009).

Then the albedos for bare ground are specified from:

$$\alpha_{\psi,bare} = \frac{\alpha_{\psi,200m} - (veg)\alpha_{\psi,veg} - f_{urb}\alpha_{\psi,urb}}{(1 - veg - f_{urb})}$$

## EMISSIVITY

The emissivity of the non-urban portion of the land surface can be written as:

$$\varepsilon = (veg)\varepsilon_{veg} + (1 - veg)\varepsilon_{bare}$$

in which  $\varepsilon_v$  is the emissivity of vegetation, obtained from:

$$\varepsilon_{veg} = \frac{\sum_{kk=4-20; 22-23, 25-26} VF(kk) \varepsilon_{vegLU}(kk)}{\sum_{kk=4-20; 22-23, 25-26} VF(kk)}$$

with  $\varepsilon_{vegLU}(kk)$  provided by the LUT given at the end of this document. The emissivity of bare soil is calculated this way:

$$\varepsilon_{bare} = \varepsilon_{drysand} A(1 - SWI) + \varepsilon_{dryclay} (1 - A)(1 - SWI) + \varepsilon_{wetsand} A SWI + \varepsilon_{wetclay} (1 - A) SWI$$

where values for “drysand”, “dryclay”, “wetland”, and “wetclay” was provided in a table earlier.

## ROUGHNESS LENGTHS

Together with vertical stability in the atmospheric surface layer, the so-called roughness lengths for momentum and heat / moisture are the principal surface parameters included in mathematical expressions for exchange coefficients used in calculations of surface turbulent fluxes. Based on vertical profiles both observed and simulated in several studies, the processes represented by these two roughness lengths differ in nature. The *momentum* roughness length seems to be representative of a larger area and has to include the effect of orography. The *thermal* roughness length on the other hand represents more local effects and does not include the effect of orography. In GEM-Surf,  $z_{0m}$  is calculated using information on a scale larger than the grid scale, and is the single value used for each type of surface (be it water, sea-ice, glaciers, natural land, and urban areas), whereas  $z_{0T}$  is specified as a fraction of the local roughness length for momentum ( $z_{0m\_local}$ ) which is based on a look-up table (LUT) provided at the end of this document.

The general expression for the (non-local) momentum roughness length is:

$$\ln(z_{0m}) = mg \left[ ga \ln(z_{0glaciers}) + (1 - ga - urb) \ln(z_{0land}) + urb \ln(z_{0urban}) \right] \\ + (1 - mg) \left[ gl \ln(z_{0sea-ice}) + (1 - gl) \ln(z_{0water}) \right]$$

in which  $mg$  is the areal fractional coverage of land in a model grid area,  $ga$  and  $urb$  are the areal fractional coverage of glaciers and urban areas over land, and  $gl$  is the areal fractional coverage of sea-ice over water. The momentum roughness lengths for these surfaces are given by:

$$\frac{1}{\ln^2\left(\frac{z_{ref}}{z_{0glaciers}}\right)} = \frac{1}{\ln^2\left(\frac{z_{ref}}{z_{0topo}}\right)} + \frac{1}{\ln^2\left(\frac{z_{ref}}{z_{0ice}}\right)}$$

$$\frac{1}{\ln^2\left(\frac{z_{ref}}{z_{0land}}\right)} = \frac{1}{\ln^2\left(\frac{z_{ref}}{z_{0topo}}\right)} + \frac{1}{\ln^2\left(\frac{z_{ref}}{z_{0land\_loc}}\right)}$$

$$\frac{1}{\ln^2\left(\frac{z_{ref}}{z_{0urban}}\right)} = \frac{1}{\ln^2\left(\frac{z_{ref}}{z_{0topo}}\right)} + \frac{1}{\ln^2\left(\frac{z_{ref}}{z_{0urban\_loc}}\right)}$$

$$\frac{1}{\ln^2\left(\frac{z_{ref}}{z_{0sea-ice}}\right)} = \frac{1}{\ln^2\left(\frac{z_{ref}}{z_{0topo}}\right)} + \frac{1}{\ln^2\left(\frac{z_{ref}}{z_{0ice}}\right)}$$

$$\frac{1}{\ln^2\left(\frac{z_{ref}}{z_{0water}}\right)} = \frac{1}{\ln^2\left(\frac{z_{ref}}{z_{0topo}}\right)} + \frac{1}{\ln^2\left(\frac{z_{ref}}{z_{0water\_loc}}\right)}$$

The lengths for ice and water surfaces ( $z_{0ice}$  and  $z_{0water\_loc}$ ) have fixed pre-determined values, whereas the so-called *local* values for land and urban areas are averages based on estimates obtained from LUTs. The reference length ( $z_{ref}$ ) is derived from small-scale subgrid-scale orography, and  $z_{0topo}$  is the momentum roughness length associated with orography. Values for  $z_{ref}$ ,  $z_{0topo}$ , and  $z_{0land\_loc}$  are obtained from GenPhysX, whereas  $z_{0urban\_loc}$  is given by UrbanX. Because horizontal scales of turbulent mixing can be on the order of a few kms (for buoyancy-driven boundary layers), the GenPhysX and UrbanX values are calculated on a coarser-resolution grid, i.e., with 2-km grid spacing, and final values are interpolated on the 200m target grid. At this time, directional effects are not considered.

Finally, the thermal roughness lengths ( $z_{0Twater}$ ,  $z_{0Tglaciers}$ ,  $z_{0Tland}$ ,  $z_{0Tsea-ice}$ , and  $z_{0Turban}$ ) are determined from the local momentum roughness lengths, which are directly provided on the GEM-Surf computational 200m grid, either using fixed values in GEM-Surf, or from GenPhysX and UrbanX based on LUTs.

## OTHER NON-URBAN LAND SURFACE PARAMETERS

Other parameters for vegetation, i.e., the root-zone depth  $d_{rz}$ , the minimum stomatal resistance  $R_{smin}$ , and the  $\gamma_v$  and  $R_{gl}$  parameters are provided in the LUT at the end of the document. The surface emissivity for broadband longwave radiation is also provided on one of the LUTs.

All these parameters are averaged using the same approach as before, i.e.,

$$\chi = \frac{\sum_{kk=4-20;22-23,25-26} VF(kk) \chi_{vegLU}(kk)}{\sum_{kk=4-20;22-23,25-26} VF(kk)}$$

where  $\chi$  is either  $d_{rz}$ ,  $R_{smin}$ ,  $\gamma_v$ , or  $R_{gl}$ .

On the other hand, the *sand* and *clay* soil composition, as well as the drainage density ( $D_d$ ) are directly provided by GenPhysX. And the form parameter  $B$  for surface flow parameterization is set to 1. everywhere.

**Look-up table for vegetation black-sky and white-sky albedos**

<b>Type number</b>	<b>Type</b>	<b>SW <math>\alpha_{BS, veg}</math></b>	<b>SW <math>\alpha_{WS, veg}</math></b>
4	Evergreen needleleaf trees	9.6	10.6
5	Evergreen broadleaf trees	11.8	13.2
6	Deciduous needleleaf trees	11.5	12.3
7	Deciduous broadleaf trees	14.9	16.8
8	Tropical broadleaf trees	12.4	14.3
9	Drought deciduous trees	13.1	14.5
10	Evergreen broadleaf shrub	13.0	13.8
11	Deciduous shrubs	13.0	13.8
12	Thorn shrubs	13.0	13.8
13	Short grass and forbs	14.9	16.7
14	Long grass	14.9	16.7
15	Crops	17.5	19.3
16	Rice	17.5	19.3
17	Sugar	17.5	19.3
18	Maize	17.5	19.3
19	Cotton	17.5	19.3
20	Irrigated crops	17.5	19.3
21	Urban areas	12.4	13.7
22	Tundra	16.0	18.0
23	Swamp	9.2	11.0
24	Desert	----	----
25	Mixed wood forests	13.7	15.0
26	Mixed shrubs	13.0	13.8

**Look-up table for local roughness length for momentum exchanges**

<b>Type number</b>	<b>Type</b>	<b><math>z_{0m}</math> (m)</b>
2	Ice	0.001
4	Evergreen needleleaf trees	1.5
5	Evergreen broadleaf trees	3.5
6	Deciduous needleleaf trees	1.0
7	Deciduous broadleaf trees	2.0
8	Tropical broadleaf trees	3.0
9	Drought deciduous trees	0.8
10	Evergreen broadleaf shrub	0.15
11	Deciduous shrubs	0.15
12	Thorn shrubs	0.15
13	Short grass and forbs	0.02
14	Long grass	0.08
15	Crops	0.10
16	Rice	0.10
17	Sugar	0.30
18	Maize	0.20
19	Cotton	0.10
20	Irrigated crops	0.10
21	Urban areas	1.00
22	Tundra	0.01
23	Swamp	0.05
24	Desert	0.01
25	Mixed wood forests	1.5
26	Mixed shrubs	0.15

### Look-up table for vegetation parameters

Type number	Type	$d_{rz}$ (m)	$R_{smin}$	$\gamma$	$R_{gl}$
4	Evergreen needleleaf trees	2.0	250	0.04	30.
5	Evergreen broadleaf trees	3.0	250	0.04	30.
6	Deciduous needleleaf trees	2.5	250	0.04	30.
7	Deciduous broadleaf trees	2.5	250	0.04	30.
8	Tropical broadleaf trees	4.0	250	0.04	30.
9	Drought deciduous trees	4.0	250	0.04	30.
10	Evergreen broadleaf shrub	2.0	150	0.	100.
11	Deciduous shrubs	2.0	150	0.	100.
12	Thorn shrubs	2.0	150	0.	100.
13	Short grass and forbs	2.0	40	0.	100.
14	Long grass	1.5	40	0.	100.
15	Crops	2.0	40	0.	100.
16	Rice	2.0	40	0.	100.
17	Sugar	2.0	40	0.	100.
18	Maize	2.0	40	0.	100.
19	Cotton	2.0	40	0.	100.
20	Irrigated crops	2.0	40	0.	100.
21	Urban areas	1.5	150	0.	100.
22	Tundra	1.0	150	0.	100.
23	Swamp	2.0	150	0.	100.
24	Desert	4.0	500	0.	100.
25	Mixed wood forests	2.5	250	0.	100.
26	Mixed shrubs	2.0	150	0.	100.

**Look-up table for land surface emissivity in the infrared radiation band.**

<b>Type number</b>	<b>Type</b>	<b><math>\epsilon_v</math></b>
1	Water (salt)	0.99
2	Ice	0.98
3	Inland lakes	0.99
4	Evergreen needleleaf trees	0.99
5	Evergreen broadleaf trees	0.98
6	Deciduous needleleaf trees	0.96
7	Deciduous broadleaf trees	0.97
8	Tropical broadleaf trees	0.98
9	Drought deciduous trees	0.96
10	Evergreen broadleaf shrub	0.96
11	Deciduous shrubs	0.96
12	Thorn shrubs	0.96
13	Short grass and forbs	0.96
14	Long grass	0.90
15	Crops	0.97
16	Rice	0.97
17	Sugar	0.97
18	Maize	0.97
19	Cotton	0.97
20	Irrigated crops	0.97
21	Urban areas	-----
22	Tundra	0.95
23	Swamp	0.98
24	Desert	-----
25	Mixed wood forests	0.97
26	Mixed shrubs	0.96