# ALGORITHMS for LAND SURFACE CHARACTERISTICS in GEM

## INTRODUCTION

### Objective

Generate all the land surface fields the GEM atmospheric models with grid spacing greater than 1km.

### Available datasets

SRTM Digital Elevation Model (DEM). Provides information on orography between 60S and 60N.

USGS GTOPO30. Provides global information on orography. Is used here to spatially complement what is available from SRTM-DEM (i.e., it is used north of 60N and south of 60S).

USGS Global Land Cover Characteristics (GLCC) database. Provides land use / land cover information globally at a 1-km resolution.

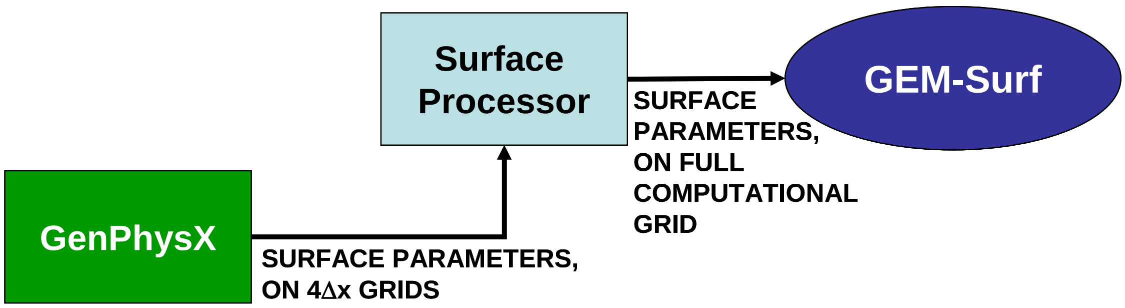
10-year climatology for the Normalized Difference Vegetation Index (NDVI) from the Moderate Resolution Imaging Spectroradiometer (MODIS), global, 1km, obtained from Rajat Bindlish at the United States Department of Agriculture (USDA).

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

SMAP Soil Texture database, global, at 1km grid spacing.

## GENERAL STRATEGY

The following diagram describes the strategy that is used to produce all the land surface fields (parameters) necessary to run the 3D atmospheric GEM.




In this figure, GenPhysX is a tool that was developed at MSC to specify surface characteristics over natural (non-urban) land areas on GEM computational grids. 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. In the approach presented here, GenPhysX produces the surface fields on grids with resolution 4 times less than the target GEM computational grid. This lower resolution is used in order to avoid GEM's surface component to provide surface fluxes that have too much variance at the model's smallest scales (i.e., less than $4\Delta x$).

The other software, the so-called "Surface Processor", gathers information from GenPhysX and from other databases in order to produce a consistent set of surface parameters on GEM's full-resolution computational grid.

## LAND SURFACE PARAMETERS

The land surface variables to initialize for GEM 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 $m^{-1}$),
- $\gamma_v$, $R_{gl}$: 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

The fractions for vegetation coverages are first specified from the USGS-GLCC land use / land cover database, as aggregated on the $4\Delta x$ GEM grids (includes the yin-yang grids used for the Canadian Land Data Assimilation System, CaLDAS). 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:

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

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

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

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

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

where $veg_{\text{crops}}$ is associated with 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

The specification of LAI on GEM's $4\Delta x$ grid is done in two steps. First, climatological LAI is specified on a global 1-km grid for each vegetation type, based on literature (look-up table – LUT), combined with information from a MODIS 1-km NDVI climatology. The second step is to upscale the LAI-1km (from the previous step) to the $4\Delta x$ grid using LULC information produced on this grid by GenPhysX.

For each LULC type specified in the RPN classification, values of mininum and maximum LAI are provided, based on literature (a table with these values is provided at the end of this document).

The NDVI climatology has already been built by our colleagues at USDA. Here, it is only required 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

For each LULC type, values of LAI at 1km grid spacing are obtained from:

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

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

The upscaling to GEM 4Δx grid is done this way:

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

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 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.

## 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., $f_{\mathrm{iso}}$, $f_{\mathrm{vol}}$, and $f_{\mathrm{geo}}$, for both the shortwave band, including visible and near-infrared radiation bands.

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

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

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

| | Isotropic (iso) | RossThick (vol) | LiSparseR (geo) |
|---|---|---|---|
| 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 $g_{\mathrm{iso}} = 1.0$, $g_{\mathrm{vol}} = 0.189184$, and $g_{\mathrm{geo}} = 1.377622$.

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. Upscale to GEM's 4$\Delta x$ grid to obtain the land surface albedos that will be used by ISBA in GEM.
D. Disaggregate the upscaled albedos into components representative of vegetation and bare soil, to be used by MISBA in GEM.

**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 $f_{\text{iso}}$, $f_{\text{vol}}$, and $f_{\text{geo}}$ 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:

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

where $\theta_Z$ is the solar angle at zenith, whereas $SW_{\text{BS}}$ and $SW_{\text{WS}}$ 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:

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

Using the two previous equations, we get:

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

which can be rewritten as:

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

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

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

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

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

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

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

**C.** Upscaling of $\overline{\alpha_{BS}}$ and $\overline{\alpha_{WS}}$ is done on GEM's $4\Delta x$ 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:

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

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), and $\alpha_{\psi,\mathrm{bare}}$ , $\alpha_{\psi,\mathrm{veg}}$ are the ground and vegetation albedos (for either direct and diffuse radiation).

In the event that a larger fraction of land is covered by vegetation (*veg* > 0.1), 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 ($\alpha_{\mathrm{drysand}}$) | 0.95 ($\varepsilon_{\mathrm{drysand}}$) |
| wet sand | 0.24 ($\alpha_{\mathrm{wetsand}}$) | 0.98 ($\varepsilon_{\mathrm{wetsand}}$) |
| dry clay | 0.15 ($\alpha_{\mathrm{dryclay}}$) | 0.95 ($\varepsilon_{\mathrm{dryclay}}$) |
| wet clay | 0.08 ($\alpha_{\mathrm{wetclay}}$) | 0.97 ($\varepsilon_{\mathrm{wetclay}}$) |

The bare ground albedos are thus:

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

in which $A = sand/(sand + clay)$ and $SWI = (w_{1cm} - w_{wilt})/(w_{sat} - w_{wilt})$ is the so-called soil wetness index, where $w_{1\mathrm{cm}}$ 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 vegetation part of the grid are obtained from:

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

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:

$$\alpha_{\psi,veg} = \frac{\sum\limits_{kk=4-20;21-23,25-26} VF(kk)\,\alpha_{\psi,vegLU}(kk)}{\sum\limits_{kk=4-20;21-23,25-26} VF(kk)}$$

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:

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

## EMISSIVITY

The emissivity 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:

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

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 stabililty 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, $z_{0m}$ 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:

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

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

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

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

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

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

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. At this time, directional effects are not considered.

Finally, the thermal roughness lengths ($z_{0Twater}$, $z_{0Tglaciers}$, $z_{0Tland}$, $z_{0sea-ice}$, and $z_{0Turban}$) are determined from the local momentum roughness lengths, which are directly provided on the GEM's $4\Delta x$ grid, either using fixed values in GEM, or from GenPhysX based on LUTs.

## OTHER 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.,

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

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 (on the $4\Delta x$ grid). And the form parameter $B$ for surface flow parameterization is set to 1. everywhere.

**Look-up table for vegetation minimum and maximum LAI**

| Type number | Type | $LAI_{min}$ | $LAI_{max}$ |
|---|---|---|---|
| 4 | Evergreen needleleaf trees | 5.0 | 5.0 |
| 5 | Evergreen broadleaf trees | 6.0 | 6.0 |
| 6 | Deciduous needleleaf trees | 0.1 | 5.0 |
| 7 | Deciduous broadleaf trees | 0.1 | 5.0 |
| 8 | Tropical broadleaf trees | 6.0 | 6.0 |
| 9 | Drought deciduous trees | 4.0 | 4.0 |
| 10 | Evergreen broadleaf shrub | 3.0 | 3.0 |
| 11 | Deciduous shrubs | 0.5 | 3.0 |
| 12 | Thorn shrubs | 3.0 | 3.0 |
| 13 | Short grass and forbs | 0.5 | 1.0 |
| 14 | Long grass | 0.5 | 2.0 |
| 15 | Crops | 0.1 | 4.0 |
| 16 | Rice | 0.1 | 4.0 |
| 17 | Sugar | 0.1 | 4.0 |
| 18 | Maize | 0.1 | 4.0 |
| 19 | Cotton | 0.1 | 4.0 |
| 20 | Irrigated crops | 0.1 | 4.0 |
| 21 | Urban areas | 0.5 | 2.0 |
| 22 | Tundra | 0.1 | 2.0 |
| 23 | Swamp | 4.0 | 4.0 |
| 24 | Desert | 0.0 | 0.0 |
| 25 | Mixed wood forests | 3.0 | 5.0 |
| 26 | Mixed shrubs | 3.0 | 5.0 |

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

| Type number | Type | SW $\alpha_{BS, veg}$ | SW $\alpha_{WS, veg}$ |
|---|---|---|---|
| 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**

| Type number | Type | $z_{0m}$ (m) |
|---|---|---|
| 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) | $R_{smin}$ | $\gamma_v$ | $R_{gl}$ |
|---|---|---|---|---|---|
| 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.**

| Type number | Type | $\varepsilon_v$ |
|---|---|---|
| 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 |