

# 3D phenomena modeling in GRASS: implementation and applications

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## Abstract

Many environmental phenomena such as atmospheric, geologic and water-related processes interest and develop in complex 3D domains. Often, the same phenomena interact with the landscape and closely depend on the features of the ground surface which are the classical 2D information managed by GISs. GRASS 5 supplies the capability to manage and analyse truly three-dimensional data, therefore mathematical models can be implemented to describe and simulate such phenomena. A set of 3D raster modules is available and under development. Functionalities for data import and export in and from the GRASS 3D raster format along with the capability to transfer 2D information into the 3D space, a three-dimensional map algebra support and visualization tools are available. This paper presents an introduction to the GRASS 3D raster capabilities and the currently available modules, a simple example is also provided.

## 1. Introduction

The knowledge of the processes involving the environment is becoming more and more complete together with the capability to analytically describe such processes. Physical phenomena such as atmospheric, geologic and water-related ones evolve and develop within a 3D space. Moreover, their behavior depends on the features of the land surface and on the interactions between the surface and the whole 3D domain and on the fluxes exchanged through the land surface. Many of such environmental phenomena can be described and analyzed through models. A wide range of models are nowadays available allowing to take into account the spatial variability of the phenomena. Nevertheless many models are, quite often, based on bidimensional mathematical formulations. Generally, the bidimensional approach follows a simplification of the theory behind the phenomenon: the complexity of the theory itself and/or the difficulty to manage a complex theory push toward simplifications. In other cases the simplification is due to the lack of tools suppling an appropriate environment where it is possible to handle 3D information.

The GRASS (Geographic Resources Analysis Support System) GIS provides the capability to manage and analyse truly three dimensional data and therefore the possibility to implement 3D models directly using and within a GIS. The advantages in having volume analysis capabilities integrated within a GIS environment are many. The spatial information, intrinsically associated to the data, are

managed together the data itself which can be therefore placed in the 3D domain where topological relations can be established between data. The volume representation is based on the definition of the 3D raster cell: the volume pixel (voxel) is the element used to discretize the domain.

GRASS supplies an internal tool to perform 3D visualization based on the OpenGL libraries. The possibility to use an external visualization software, such as Vis5D+, is also provided along with the capability to directly import Vis5D+ data into GRASS.

## **2. 3D environmental phenomena and dimensions in GIS**

The analysis of 3D processes and the study of volume domains are of interest for a more and more wide range of scientific fields. Geology, soil and water-bearing sciences along with atmospheric and pollution diffusion processes modeling can be reported as some of the major application fields. As examples of applications [1], [2], [3] and [4] can be cited. As mentioned, the description and the analysis of environmental phenomena is based on the knowledge of the physics of the processes and on the definition of theories that can be used to model the processes. Most of the models nowadays implemented in GISs follow the 2D approach. The management and the study of information on the land features such as morphology and land-use along with the evaluation of the fluxes exchanged through the ground-atmosphere interface and the handling of measured data are well known topics in GIS applications. Such information can be completely described using a 2D approach and classic 2D GIS capabilities and techniques. These information become of high interest when a 3D model is developed since they can be considered as input, as well as boundary conditions, for the model itself. Since the most of the GISs today available provides a "so called" 3D capability it is the case to briefly underline what, here and into GRASS, is meant with three dimensional.

- 2D** Only planimetric spatial information (i.e. with two coordinates) can be handle, e.g. raster maps;
- 2D 1/2** altimetrical information are allowed, but it is not possible to assign more than one value to the same pair of planimetric coordinates, e.g. visualization of DTMs;
- 3D** each entity is given 3 spatial coordinates, the altimetrical information is no longer managed as data attribute, it is possible to have more than one value given a pair of planimetric coordinates;
- 4D** a time coordinate is given to each entity along with the three spatial coordinates.

## **3. 3D modeling: the GRASS 3D-raster tools**

A brief introduction of the GRASS 3D raster capabilities is given here. This part focuses on the way 3D data is handled in GRASS and on the available modules; it should help to outline the main differences with the GRASS 2D features which are assumed as known. The manual pages of the modules listed below and the "GRASS developers' Manual" [5] are the essential references to complete the

description and the understanding of how this part of GRASS works. The source code of modules and scripts can be found in the following sub-directory of the GRASS source code tree:

```
GRASS_SRC_PATH/src.contrib/GMSL/g3d
```

while the "G3d libraries" can be found in:

```
GRASS_SRC_PATH/src/libes/g3d
```

A sample data set is also available at:

```
http://grass.itc.it/grid3d/grass5grid3d\_sample.tar.gz
```

The GRASS raster approach is based on the discretization of the domain through elements with constant geometric features, i.e. resolution, within the whole domain. As for 2D raster the bi-dimensional space is described using pixel, for the 3D GRASS rasters the voxels are used to describe the volume. The difference is that while to discretize a surface only one pixels layer is needed, to discretize a volume one or more layers have to be considered. The number of layers depends on the vertical resolution of the voxels, i.e. on how "dense" the discretization is. Every layer "sees" the planimetric resolution of the voxels and therefore has the same planimetric features of a 2D raster (i.e. it is formed by rows and columns of elements). Since the voxels resolution is constant within the volume, the volume can be seen as a parallelepiped. To completely describe a discretized volume is therefore necessary to give the coordinates of the volume boundaries.

There is not the equivalent 3D version of the well known GRASS location. Once a classic location has been created the user can define a new 3D region, belonging to the location. When a new 3D region is created the user has to specify, along with the usual planimetric limits and resolution, the top and bottom limits and the vertical resolution. The commands that allow the user to create and manage the 3D region are:

<code>g3.createwind</code>	allows the user to create the default region;
<code>g3.region</code>	allows the user to change the settings of the current region through a prompt similar at the one of <code>g.region</code> ;
<code>g3.setregion</code>	allows the user to change the region in a simple command line.

Creating 3D region produces the files: `WIND3` and `DEFAULT_WIND3` where the information regarding the volume boundaries and the voxels resolution is stored, for the current and the default regions respectively.

The directory structure used for the 3D raster files is not the same of the GRASS standard. In GRASS a raster map is made up of different files. In the current 5.0 and 5.3 versions these files have the same name of the map and are located in different directories depending on the information type stored in the files. For the 3D raster maps, as for the new GRASS 5.7 vector maps, a unique directory, with the same map name, contains all the files composing that map. This structure is sketched in figure 1.

```

$GISDBASE/$LOCATION/
|--PERMANENT
: |--DEFAULT_WIND3
: |..
: `..
`--$MAPSET
|--grid3
: |--3d_raster_map_name
: |--cell
: |--cellhd
: |--range
: |--cats
: `--dsp
|--
`--

```

**Figure 1:** Directory structure and files for GRASS 3D raster maps

Data input is possible through two different tools, depending on how the data were collected or generated. Input data can be gridded or sparse data. The file containing gridded data has to be written in ASCII format, in the first rows of the file, the header, the geometric information are stored: volume boundaries and voxels resolution are written one per row. The data values are written below the header: for each layer the data are written in a matricial format, i.e. rows time coloumns, the first layer is the lower and the last is the topmost. The structure of a 3D site file is similar to the 2D one. The difference is that on each line all the three coordinates have to be specified before the data value is given.

```

r3.in.ascii  allows the user to input gridded values;
s.to.rast3   allows the user to input sites values.

```

Both this commands generate a 3D raster map in the GRASS format: a `cell` binary file is created to store data values along with a `cellhd` text file. The relevant information of this file is reported in figure 2. In bold-faced are reported the items that do not appear in the header file of a 2D raster map. They refer to the “Top” and “Bottom” geometric limits of the volume, to the “number of levels” used to verically discretize the volume and to the “verical resolution“ ofthe layer, i.e.of the voxel.

Proj:	<b>Bottom:</b>
Zone:	nofRows:
North:	nofCols:
South:	<b>nofDepths:</b>
East:	n-s resol:
West:	e-w resol:
<b>Top:</b>	<b>t-b resol:</b>

**Figure 2:** Main items in the header file of a GRASS 3D raster `cellhd` file

A set of modules to perform 3D data analyses is also provided. Through these modules it is therefore possible to implement models and algorithms to study and characterize many 3D environmental processes. A module performs 3D spatial interpolation, while the other supplies a powerful tool to develop spatial dependent analyses being the 3D version of the `r.mapcalc` module.

<code>s.vol.idw</code>	performs 3D spatial interpolation through the “Inverse Distance Weight” algorithm;
<code>s.vol.rst</code>	performs 3D spatial interpolation using the “Regularized Splines with Tension”;
<code>r3.mapcalc</code>	implements a 3D map calculator supporting algebraic, trigonometric and binary operators and functions along with a 3D neighborhood modifier.

All these modules act on the entire 3D region, this could not always be necessary or the right approach. A dedicated module is therefore available to allow these modules to act only on a part of the 3D region.

<code>r3.mask</code>	allows the user to specify a 3D raster map that will be used to “mask” the domain. This raster can contain only binary values which are used to select the voxels where the analysis has to be performed.
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The results can be visualized through a GRASS viewer based on the OpenGL graphic engine. It is possible to navigate into the volume, using the mouse to rotate the data along the three axes and to zoom the data in and out. Data are visualized through isosurfaces that have to be previously generated through a dedicated module. It is possible to choose how many isosurfaces have to be used to describe the data or the distance between the isosurfaces. The isosurfaces can be generated for the entire values range or on a its sub-range. It is also possible to export 3D rasters in the Vis5D+ format. Vis5D+ is a viewing tool, initially developed for meteorological data, that allows sophisticated and powerful isosurfaces and volume visualizations.

<code>r3.mkdspf</code>	produces a “display file” where the information needed to display the isosurfaces are stored;
<code>r3.show.dspf</code>	displays the isosurfaces previously calculated;
<code>r3.out.v5d</code>	export the 3D raster map to Vis5D+.

Since the validation of the analysis results can not be performed only through visualization, the possibility to save data in ASCII format is given. In this way the values can be directly read by the user and the file itself can be used as input for various external softwares. Two modules are available to allow data exportation in the gridded format and the generation of a site file from a 3D raster map. Producing a site file from a raster map can be useful since NVIZ supports sites files with 3D coordinates

GRASS capabilities to manage 3D geographic information are already very powerful taking into account that such functionalities are integrated and available within a GIS. Anyway the available modules provide only the basic and essential functions for volume analyses. The possibility to specify, within the volume, boundaries surfaces, different from the volume sides, is a future need along with the possibility to allow `r3.mapcalc` to use also 2D rasters. The internal visualization tool could

be improved or its functionalities could be added to NVIZ. Since many phenomena heavily depend on the boundary conditions, which are defined on 2D surfaces, the interface toward the 2D raster maps should also be implemented. GRASS supporting 4D data analysis and storage would be another important improvement in the future development projects.

#### 4. Application: daily cycle of air potential temperature upon a slope

A simple example of 3D data analysis exploiting the GRASS 3D raster tools is provided here. The aim of this part is to give a brief description on how a 3D model, describing an environmental phenomenon, can be implemented using GRASS.

The atmosphere is an intuitive application field where GRASS capabilities can be tested and applied to model 3D processes. The spatial and time evolution of many atmospheric phenomena depend on a wide set of physical quantities. The interaction with the ground surface plays, moreover, a relevant role in the developing of the processes. The characterization, along a time period of 24 hours within a 3D domain, of the air *potential temperature* is carried out. Potential temperature is a temperature measure widely used in the atmospheric applications. It is defined as the temperature an element of air volume would have if lead to a reference pressure  $p_0$  (1000 hPa), along an adiabatic transformation. Absolute temperature  $T$  and potential temperature  $\theta$  are tied by the equation:

$$\theta = T \left( \frac{p_0}{p} \right)^{\frac{\Re}{C_p}} \quad (1)$$

where  $p$  is the atmospheric pressure,  $\Re$  the gas constant for dry air and  $C_p$  is the specific heat at constant pressure.

The potential temperature can be expressed as the sum of a linear function of the  $z$  coordinate and an anomaly term,  $\Delta\theta$ , related to the sensible heat flux from the slope surface along the direction  $n$  normal to the slope. This relation had been defined by Defant [7] and is expressed by the equation:

$$\theta = A + \Gamma_d z + \Delta\theta(n) \quad (2)$$

where  $\Gamma_d$  is the potential temperature vertical gradient in standard atmospheric conditions. The anomaly of potential temperature is:

$$\Delta\theta = C e^{-n/\ell} \cos(n/\ell) \quad (3)$$

What is important here is that the potential temperature  $\theta$  depends on two geometric quantities: the vertical height  $z$  and the coordinate  $n$ , measured along the direction normal to the slope, and on the physical quantity  $C$  which is a function of the heat flux exchanged between the ground-atmosphere interface. While the two geometric quantities can be evaluated from the ground morphology (i.e. the DTM), the value of  $C$  depends on the sensible heat flux. This flux can be evaluated solving the heat fluxes balance at the ground level which mainly depends on the solar radiation and on the land coverage. Since the value of the solar radiation depends on the solar position, the equation 2 is time dependent. The daily cycle is due to the interaction between the conditions of the valley air, which

are different during the day-time and during the night-time, and the air conditions that develop in the atmospheric layer closer to the slope surface where the time variability of the heat fluxes exchanged at the surface drives the process.

To implement in GRASS a procedure to describe the time and space variability of the potential temperature the following quantities have to be know:

<i>quantity</i>	<i>description</i>	<i>domain dimension</i>	<i>varies in</i>
$z$	distance from the ground, along the vertical direction	volume, 3D	space
$n$	distance from the ground, along the normal direction	volume, 3D	space
$C$	anomaly of potential temperature, $z = 0$	surface, 2D	time, space

In equation 2, the values of  $A$ ,  $\Gamma_d$  and  $\ell$  can be assumed constant in this example, without loss in generality and in accuracy.

The value of the potential temperature  $\theta$  is computed in each voxel over the ground surface. The 3D domain is designed to reproduce a portion of a mountain valley, while the information on the land coverage came from the land use map. The quantities that played a role in the process and how they had been managed in GRASS are reported in table 1.

<i>map</i>	<i>dimension</i>	<i>GRASS module</i>	<i>equation</i>	<i>dependences</i>
$z$	3D	<code>r3.mapcalc</code>	<i>mapcalc function</i>	DTM
$n$	3D	<code>r3.isosurf [3]</code>	see [3]	DTM
land coverage	2D	<code>r.*</code>	-	-
solar radiation	2D	<code>r.sun</code>	see [6]	DTM
$C$	2D	<code>r.mapcalc</code>	see [3]	land coverage, solar radiation

Table 1: Main quantities in the implementation of the physical model in GRASS

Once all the quantities in table 1 are known it is possible to implement equation 2 using the functionalities of `r3.mapcalc` to produce a 3D raster map where each cell is assigned the value of the potential temperature. To describe the potential temperature time variability the solar radiation has been evaluated every hour, i.e. 24 maps had been generated and used to produce the correspondent map of the potential temperature at a give hour of the day. In figure 3 is reported the sequence of the daily cycle of the potential temperature upon a slope. In figure 4 is reported the Vis5D+ visualization of one of resulting maps.

The procedure described has been reported here as an example of how a 3D model can be implemented in GRASS and therefore some aspects of the theory behind the process has been not included. It is useful here to underline two topics that can help to better understand the procedure from a more technical perspective. As seen, the value of the potential temperature in each voxel of the volume depends on the quantities  $n$  and  $C$ . For a given cell it is therefore necessary to evaluate its distance from the ground surface along the direction normal to this surface. To solve this problem a new GRASS 3D module had been developed, (`r3.isosurf`). Given the DTM (a 2D map, i.e. a surface) the module,

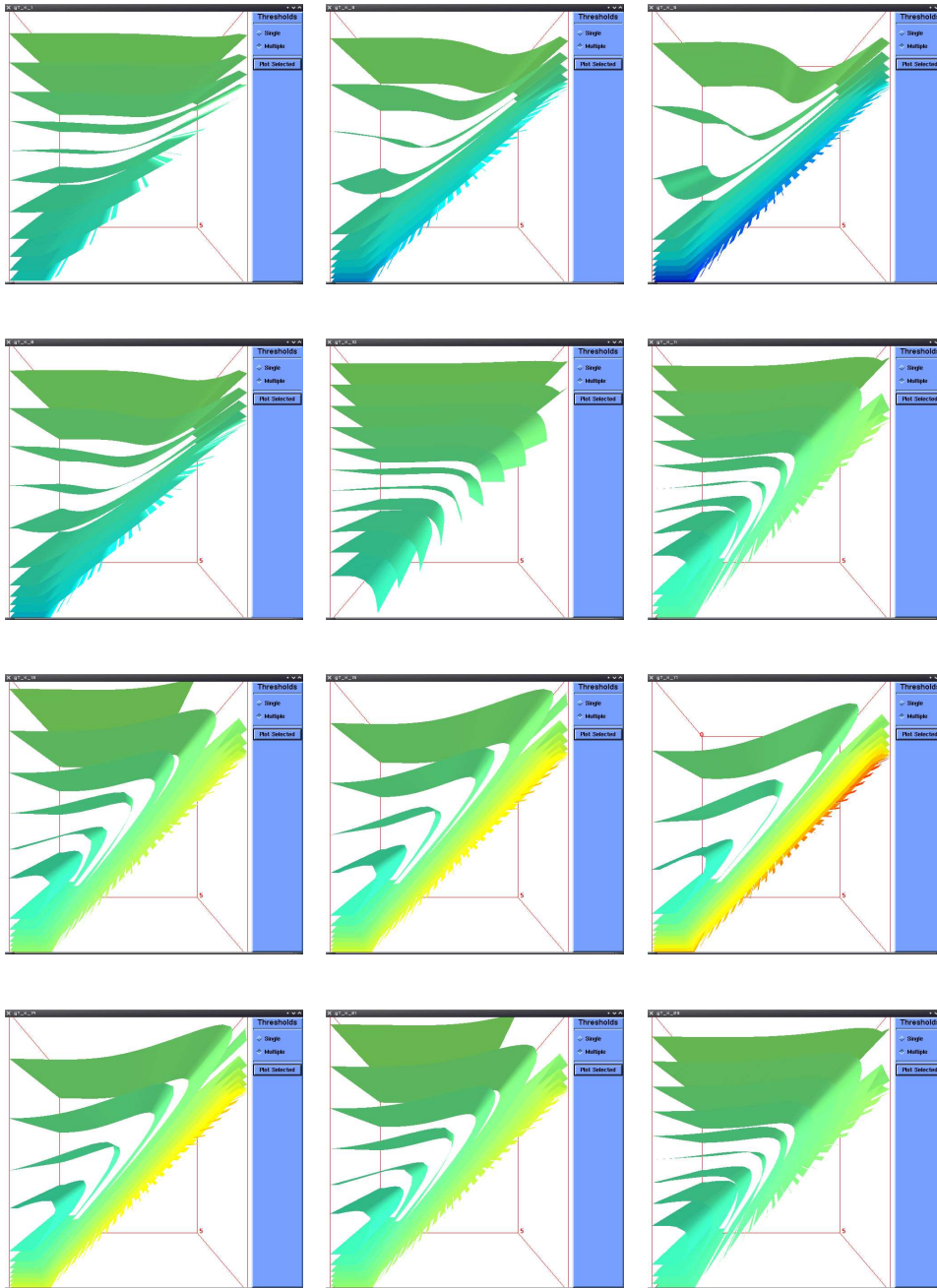


Figure 3: Cycle of potential temperature upon a slope during a 24 hours time period



searches which cell of the ground surface is closest to the current volume element and evaluates their distance. This value is then updated using the slope and aspect information of the ground surface cell, to obtain a more accurate estimation of the  $n$  value. The output of the module is a 3D raster map where each cell contains this value. For each volume element the coordinates of the closest ground surface cell are stored in an auxiliary 3D raster map. The estimation of the  $C$  quantity has also to be performed. Since  $C$  represents the potential temperature at the ground level, its values can only be stored and managed through a 2D raster map. Equation 2 applies to each volume element, i.e. has to be implemented using 3D GRASS tools and its values have to be stored and managed through a 3D raster map. For a given volume element the  $C$  value that has to be considered refers to the ground surface cell which lay on the direction of  $n$ . The auxiliary output map of the module `r3.isosurf` is therefore used to assign each 3D element the value of  $C$  referring the closest ground surface cell. In this way bidimensional information is “transferred” to the 3D space. A more detailed description on the procedure for the estimation of the  $n$  coordinate and on the theory behind the physical model can be found in [8].

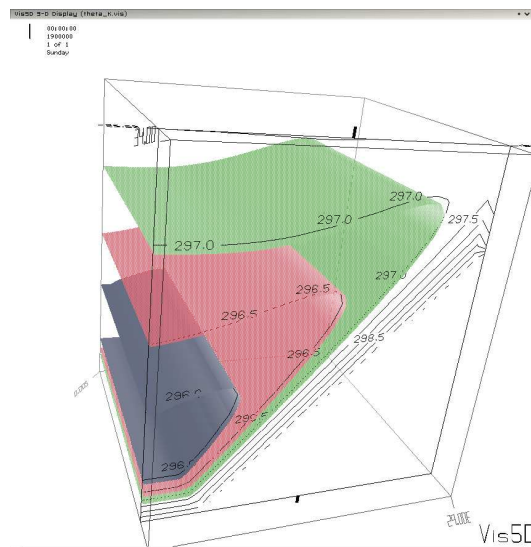


Figure 4: Potential temperature upon a slope at one time position of the 24 hours cycle, see figure 3

## 5. Conclusions

The GRASS features to manage 3D data extend the capabilities and the functionalities of this GIS. The available modules already make of GRASS an advanced and powerful environment for the development of volume and 3D data modeling and analysis. One of the main advantages that GRASS offers is that the implementation of environmental phenomena can be directly performed within a GIS. Complex 3D processes, depending also on the land surface features, can be approached with relatively simplicity. So far some capabilities are not yet available: it is not possible to describe surfaces within

the volume and the support for dynamic analyses is not complete. The availability of the source code under the GNU/GPL permits the improvement and the development of GRASS.

A brief introduction to the main feature of the GRASS 3D tool has been provided along with an example describing how a 3D model for the characterization of a 3D phenomenon can be implemented in GRASS. The example highlights how bidimensional and three dimensional data and analyses can be integrated in a procedure for the estimation of the air potential temperature within a 3D domain, such as a mountain valley.

The raster approach is not the only way GRASS support 3D data, currently the new 3D vector architecture, which implements and extends 3D management and analysis functionalities also to vector data [9], is under quick and heavy development

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