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A temporal GIS for field based environmental modeling

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ABSTRACT

Time in geographic information systems has been a research theme for more than two decades, resulting in comprehensive theoretical work, many research prototypes and several working solutions. However, none of the available solutions provides the ability to manage, analyze, process and visualize large environmental spatio-temporal datasets and the investigation and assessment of temporal relationships between them. We present in this paper a freely available field based temporal GIS (TGRASS) that fulfills these requirements. Our approach is based on the integration of time in the open source Geographic Resources Analysis Support System (GRASS). We introduce the concept of a space time dataset that is defined as a collection of time stamped raster, voxel or vector data. A dedicated set of spatio-temporal tools was implemented to manage, process and analyze space time datasets and their temporal and spatial relationships. We demonstrate the temporal GIS and environmental modeling capabilities of TGRASS by analyzing a multi-decadal European climate dataset.

1. Introduction

The integration of time in geographic information systems has been an ongoing research theme for 25 years. The book *Time in Geographic Information Systems* (Langran, 1992) marked a first milestone in temporal GIS. Since then, the literature about temporal GIS concepts and related topics like spatio-temporal database models has grown rapidly. Comprehensive overviews about spatio-temporal database models and temporal GIS approaches are available in Pelekis et al. (2004), O'Sullivan (2005) and Ott and Swiaczny (2001).

The temporal GIS approach for environmental modeling that we present in this study focuses on the field based view on geographical data. We follow in our approach the field definition of Galton (2001): A spatial field is a mapping from spatial locations to values that may be any kind of data structures. The field provides a coverage of space using irreducible minimal regions, for example represented as a pixel. A mapping that assigns a value to each location at each time is called a spatio-temporal field. The distinction between an object based and field based view of geographic information is an important concept in geoinformation science. A good overview about this distinction with comprehensive theoretical work is given in Galton (2001, 2004), Goodchild and Gopal (1989) and Goodchild (1992).

Field based temporal GIS has been a key technology for integrated assessment modeling that is common in the climate change research (Christakos et al., 2001). With the availability of high resolution environmental datasets with continental to global extent containing continuous field measurements and output data from physical, chemical or statistical models, a strong need has emerged to efficiently manage, analyze, process and visualize such big data.

Several spatio-temporal environmental modeling software systems and temporal GIS solutions are available that include STempo (Peuquet and Hardisty, 2010), GeoViz Toolkit (Hardisty, 2013), PCRaster (PCRaster team, 2012), TerraME (de Senna Carneiro et al., 2013), the R environment for statistical computing (R) (R Development Core Team, 2012), TerraLib (Câmara et al., 2008), Climate Data Operators (CDO) (Schulzweida, 2013), Arc Hydro Groundwater (Aquaveo LLC, 2013) and STEMgis (Discovery Software Ltd, 2013). Most of these solutions have a dedicated purpose that is spatio-temporal visualization, statistical analysis, water management, raster time series processing or climate data analysis. Yuan (2009) stated that most temporal GIS technology developed are still in the research phase or have an emphasis on mapping. Exceptions are the TerraLib and the R environment. Because of its modular approach the R environment can be enhanced with several spatial, temporal and spatio-temporal packages. For example the *spacetime* package (Pebesma, 2012) in conjunction with packages *sp*, *xts*, *rgeos* and *raster* transform R into a feature rich spatio-temporal GIS environment with modeling, statistical analysis and visualization capabilities. However, to

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process massive datasets that do not fit into the main memory,[1] R still requires a spatio-temporal database backend and is therefore not well suited yet for large-scale field based spatio-temporal modeling. The main aim of the TerraLib class and functions library is to enable the development of new generation GIS applications. TerraLib implements the basic infrastructure for spatio-temporal analysis and modeling and supports several different spatio-temporal data types (events, mobile objects, and evolving regions) (Câmara et al., 2008). On top of TerraLib, TerraME de Senna Carneiro et al. (2013) offers the capability to model nature-society interactions, using multi-scale concepts.

None of the available solutions provide large-scale field based, spatio-temporal environmental modeling capabilities that are based on a comprehensive set of spatio-temporal GIS management, processing and analysis tools. With the exception of the R environment available solutions do not support the analysis of relationships between spatio-temporal fields that are used in environmental modeling.

The aim of this paper is to describe a field based temporal GIS, based on the Geographic Resources Analysis Support System (GRASS), to efficiently manage, visualize, process, model and analyze large spatio-temporal fields and their spatio-temporal relationships. An additional aim is the interoperability between our temporal GIS (TGRASS) and the spatio-temporal modeling and analyzing environments R and CDO as well as ParaView (Kitware Inc., 2013a). The management, analysis, modeling, processing and visualization capabilities of our approach are demonstrated by analyzing a large climate dataset provided by the European Climate Assessment and Dataset project (ECA&D).

2. Related work

The temporal GIS approach presented in this paper follows the field based world view using two and three spatial and one temporal dimension as defined in Galton (2004). A comprehensive field based temporal GIS must support different kind of fields that are common in environmental modeling. Common spatial fields may have two or three dimensions. Such spatial fields are regular gridded, irregular gridded or of object type. A continuous field that maps location to spatial objects is defined as an Object field (Cova et al., 2002). Object fields are introduced in Galton (2001) and formulated more generally in Cova et al. (2002). Regular gridded fields can be represented as raster (2D) or voxel (3D) data. Irregular gridded fields can be represented as two or three dimensional point clouds, triangulated irregular networks (TIN) or Voronoi diagrams. These kind of fields are a specific form of object fields since they are built upon vector features like points, lines and polygons. Object fields may also contain spatial objects representing for example a watershed or a viewshed.

In our study the spatio-temporal fields are organized using time stamped spatial fields. This is commonly known as a snapshot approach. It has been utilized in several temporal GIS implementations because of its simplicity and the ability to extend existing spatial GIS that are layer based. Following the snapshot approach to integrate time in a spatial GIS, time stamps are assigned to spatial fields. Hence all cells (2D or 3D) or objects in a spatial field share the same time stamp. We will use the term *snapshot* and *time stamped spatial field* interchangeably in our paper. The concept of space time datasets was introduced to efficiently manage time stamped spatial fields. Space time datasets represent spatio-temporal fields in TGRASS. They are defined as a collection of time stamped spatial fields (snapshots) from which they derive their spatial and temporal extent. The common snapshot approach was extended in TGRASS so that each time stamped spatial field can have a different spatial and temporal extent. Temporal as well as spatial relationship computation between time stamped spatial fields is supported to allow the investigation of spatio-temporal interactions between them.

Space time cubes were introduced with two spatial (x, y) and one temporal (t) dimension. Space time cubes are often utilized to analyze and visualize space time paths resulting from the movement of individuals or objects in space and time. The space time cubes in TGRASS represent spatio-temporal fields, build upon three dimensional pixels (voxels). Forer (1998) denoted these kind of voxels as taxels to emphasize the specific nature of the time dimension. We denote this three dimensional spatio-temporal field representation as space time voxel cube. It can be seen as a special case of a space time dataset with restricted properties. The benefit of space time voxel cubes is the availability of several tools in GRASS that can perform spatio-temporal operations on them, for instance spatio-temporal map calculation as defined in Jeremy et al. (2005). Mitasova et al. (2011) utilized the voxel capabilities of GRASS to analyze time series data.

2.1. *Time in space time datasets*

Several different models of time in geographic information systems have been developed. Models of time can be linear or cyclic, discrete or continuous, supporting branching or multiple perspectives. A comprehensive overview about different times in GIS is given in Frank (1998).

A field based temporal GIS must represent how fields are measured in time. Temperature for example is measured at time instances but the mean temperature is computed for time intervals. Precipitation and Greenhouse Gas (GHG) emissions are measured in time intervals. The system must be aware of calendar time to manage and analyze interaction between measured fields. Environmental models may use time for simulation with no fixed reference, hence relative time must be supported.

TGRASS uses the concept of linear, discrete time represented by time instances and time intervals. Time intervals and time instances represent the time stamps of spatial fields. The interval time model supports the occurrence of gaps between intervals. Time intervals are allowed to overlap or contain each other and can contain time instances. Time intervals can be unequally spaced. Time is measured using the Gregorian calendar time, also called absolute time, conform to ISO 8601[2] and as relative time defined by an integer and a unit of type year, month, day, hour, minute or second. The smallest supported temporal granule is a second. The definition of absolute and relative time follows the temporal database concepts collected in Dyreson et al. (1994).

Time intervals in our approach are designed to easily detect gaps. Intervals consist of a start time instance and an end time instance. The end time is not part of the time interval and represents the start time of a potential successor. Hence the time interval is a left closed right open interval. In case the end time of an interval is the start time of a second interval no gaps exist between them. Space time voxel cubes support only non-overlapping time intervals.

2.1.1. *Temporal granularity*

An important concept in temporal databases is the temporal granularity. A glossary about temporal granularity is available in

[1] With the exception of the *raster* package.

[2] http://en.wikipedia.org/wiki/ISO_8601.