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A pole-oriented discrete global grid system: Quaternary quadrangle mesh

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ABSTRACT

In addition to providing services for mid and low latitudes, global Geographic Information System (GIS) should provide services for high latitudes; these services include climate monitoring, energy exploitation in the polar regions. An improved Discrete Global Grid System (DGGS) could serve as a foundation for efficient indexing, visualization and analysis of the ever-expanding global spatial data in the global GIS environment. However, existing DGGSs have problems with balancing polar and other regions, including serious cell area and shape distortion in the polar regions or precision loss when applying the systems to existing geographical data. Here, a new pole-oriented DGGS, the Quaternary Quadrangle Mesh (QQM), is proposed. This DGGS uses semi-hexagon (a type of quadrangle) grids in the polar regions and rectangular grids elsewhere. The semi-hexagonal partitioning in the polar regions reduces the redundancy of the polar data and avoids the polar singularities that frequently exists in DGGSs. A consistent encoding-decoding scheme and a uniform adjacent search algorithm were constructed by considering that polar cells and other cells form a coherent unity in the QQM, which has a hierarchical structure. The experimental results demonstrate that the QQM performs better than the recently proposed Degenerate Quadtree Grid (DQG) regarding geometrical distortion, and encoding-decoding and adjacent search efficiency. The QQM can satisfy the requirements for global data indexing and visualization, especially in the polar regions.

1. Introduction

Schemes for tessellating the curved surface of the earth and for data indexing and visualization must improve to contend with the ever-expanding pool of global spatial data (Goodchild et al., 2012). An improved Discrete Global Grid System (DGGS) could serve as a foundation for efficiently indexing and visualizing the large pool of global spatial data in the global Geographic Information System (GIS) environment. In addition to providing services for mid and low latitudes, global GIS should provide services for high latitudes. These services include, for example, monitoring the impacts of climate change on polar glaciers and sea levels around the world, and exploiting the energy and ecology resource in polar regions. Thus, a DGGS with excellent data indexing and visualization properties in polar and other regions is needed.

DGGS researches strive to accurately express the global surface, efficiently index global data and smoothly visualize global data. However, currently, researchers have only achieved limited success when balancing polar and other regions. Most existing DGGSs are based on regular polyhedras or geographic coordinate systems. The latitude–longitude grid cell areas and shapes are severely distorted in the polar regions. Regular polyhedral DGGSs alleviate this distortion. However, most of their cell edges do not coincide with the meridians and parallels. Thus, polyhedral DGGSs are difficult to apply to some types of existing geographical data that are based on the geographic coordinate systems around the earth.

In this paper, a pole-oriented discrete global grid DGGS, refered to as the Quaternary Quadrangle Mesh (QQM), is proposed to address exsisting DGGS deficiencies. The QQM reduces cell distortion and data redundancy in the polar regions. All of the QQM grid cells are quadrangles, semi-hexagons (in the polar regions) or rectangles (elsewhere). The QQM is seamless and the polar grid edges match the non-polar grid edges. Quadrangular subdivisions, which can be represented as squares or rectangles on a map projection, are easier to manage with computers than other geometric shapes (Ottoson and Hauska, 2002). Data can be stored at different levels of resolution and all nodes can be manipulated by the same programs and algorithms in the QQM's regular hierarchical structure (Tobler and Chen, 1986). Because multi-dimensional codes (level, row, column) degrade the system performance (Mokbel et al., 2003), they are mapped as 1-Dimensional codes in the QQM. The conversion between a QQM address code and its geographic coordinates is

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simple, which is advantageous for using existing spatial data. In addition, the QQM has simple adjacencies, which are the basis for efficient spatial processing (including indexing and range searching) (Gold and Mostafavi, 2000).

The partitioning method, the encoding and decoding scheme, and the adjacent search algorithm are presented in Section 3. The performance of the QQM is compared with the performance of the DQG in Section 4. In addition, the application of the QQM for organizing and visualizing global spatial data is provided in Section 5. Overall, the experimental results demonstrated the following: (1) the cell shapes and areas of the QQM are analogous; (2) the efficiencies of encoding, decoding, and adjacent searches in the QQM are greater than in the DQG; and (3) the visualization of global data based on the QQM is smooth.

2. Related work

Regular polyhedral DGGSs have been studied by several researchers. For example, the Spherical Quaternary Triangle (SQT) was proposed by Fekete and Treinish (1990); the Quaternary Triangular Mesh (QTM) was proposed by Dutton (1997); a hierarchical tessellation mesh for a WGS-84 ellipsoidal surface that was based on quaternary triangular meshes was proposed by Bai et al. (2011); recursive diamond subdivision grids were proposed by White (2000); and hexagonal DGGSs were used by several authors (Sahr, 2008; Tong et al., 2010; Vince, 2006; White et al., 1992). These regular polyhedral DGGSs have excellent properties, including a hierarchical structure, similar cell areas and shapes, and global addressability. However, mapping from a polyhedra to a sphere is a complex process because most cell edges do not coincide with meridians or parallels in the polyhedral DGGS. Thus, it is difficult to apply polyhedral DGGSs to existing spatial data that are based on the geographic coordinate system without a costly conversion process. However, this conversion process results in a loss of precision. Therefore, polyhedral DGGSs cannot satisfy the organization and updating requirements of global spatial data.

The traditional latitude–longitude grid system, includes a relationship between the cell edges and the geographic coordinate system and simple data storage and processing (Gregory et al., 2008). Thus, this DGGS has been widely used by researchers (Albergel et al., 2010; Fekete and Treinish, 1990; Lindstrom and Pascucci, 2001; Samet and Sivan, 1992) and agencies (such as the US Geological Survey, which provided the GTOPO30 data). However, the latitude–longitude grid cell areas become smaller towards the poles. In addition, the shape of the cells becomes increasingly distorted and turn into triangles at the poles. The North and South poles are points on the surface of the earth, but map to lines on the latitude–longitude plane (Sahr et al., 2003). Each of these polar singularities has an unique latitude but an uncertain longitude. The irregular cell areas and shapes decrease the manipulation accuracy and result in data redundancy. For example, the elevation of the poles is repeated 43,200 times in GTOPO30 (U.S. Geological Survey, 1999).

Attempts have been made to create adjusted latitude–longitude grid systems to obtain more consistent cell sizes. For example, by considering the curvature of the earth, Ottoson and Hauska (2002) proposed Ellipsoidal quadtrees (EQT) with latitudinal intervals that increase form the equator to the pole and longitudinal intervals that reamin the same. The National Imagery and Mapping Agency (NIMA, 2003) provides Digital Terrain Elevation Data (DTED) with longitudinal intervals that increase from the equator to the poles while the latitudinal intervals remain the same. Bjørke et al. (2003) and Bjørke and Nilsen (2004) proposed a constant-area quadrilateral grid system (FFI) with latitudinal and longitudinal intervals that change simultaneously. Beckers and Beckers (2012) used similar latitude and longitude adjustments of cell edges to achieve cell regions of approximately equal areas. Although these approaches yeilded more regular cell areas, the shapes of the cell region became more irregular, contained more complex cell adjacencies, or both. Ma et al. (2009) proposed a square DGGS based on their parallels plane projection. This method resulted in grid cells that were approximately equal in area and shape. However, broken grids appeared near the two polar regions and in the converging areas of the eastern and the western hemispheres.

Most of the adjusted latitude–longitude grid systems have complex initial division rules. Two separate index mechanisms must be implemented, one for the base level and one for lower levels (Ottoson and Hauska, 2002). No unified equation exists for converting between the latitude–longitude and address code, which complicates encoding and decoding because several different types of conversions must be implemented for the grids at different locations. These adjusted latitude–longitude grid systems are difficult to use for organizing and visualizing global multi-resolution data.

To address some of these difficulties, Sun et al. (2009) proposed the Degenerate Quadtree Grid (DQG) with longitudinal intervals that increase regularly from the equator to the poles and latitudinal intervals that remain the same. The longitudinal interval of one row in the DQG is half or twice as large as its adjacent row. The DQG has attractive properties, including a hierarchical structure, convergent geometrical distortion, and simple cell adjacencies. The DQG has solved the problem (to some extent) of large

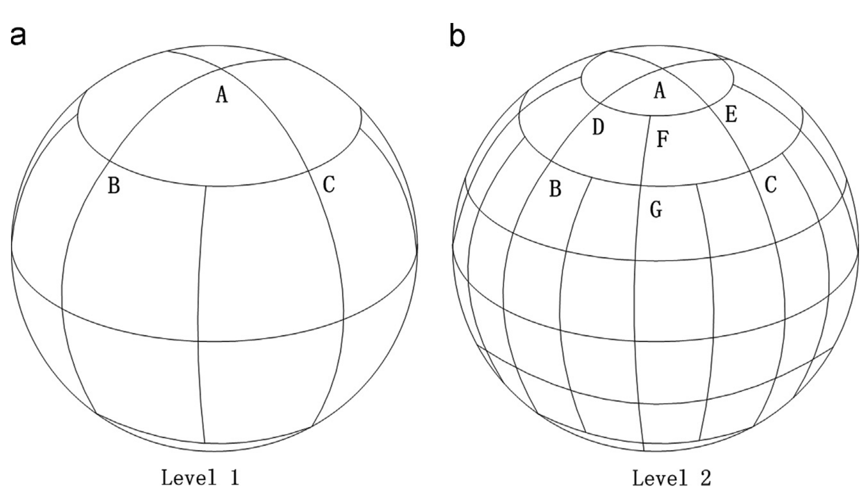

Fig. 1. The DQG grid shapes are transformed to triangles in the polar region.