Challenges in the visualization of a two-dimensional mantle dynamics simulation using one billion tracers

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Abstract

We have developed a two-dimensional numerical method to model the process of slab subduction using a marker-cell method together with a conservative finite-difference method that accounts for hydration and partial melting in the thermal, chemical, mechanical, rheological, and petrological domains. The marker-in-cell approach is ideal for this complex geophysical problem [1] because it allows for the resolution of extremely small-scale lithological and thermal structures produced as a result of the intense mechanical mixing of different rocks [2,3]. A two-dimensional simulation employing over one billion tracers with multiple fields presents many visualization hurdles. In this paper we discuss the methods that we have used to interpret the data from this simulation including high-resolution visualization on a display wall and a web-based visualization system that we have developed using an hierarchical data format to achieve sub-second response times when accessing extremely large datasets.

Keywords: Geophysics; Convection; Multicomponent; Visualization; Display wall; Web interface

1. Introduction

Thermal-chemical convection with multi-component systems is quickly becoming a hot field in computational geodynamics because of increased recognition of the role played by volatiles and melts. The current generation of shared-memory supercomputers has allowed us to perform numerical simulations of a subduction zone using up to one billion markers in two dimensions. The process of subduction is extremely complex from a geophysical standpoint and inherently difficult to model. A subduction zone mandates a multicomponent, multiphase model that encompasses lithological variability of subducted rocks and hydration and partial melting in the thermal, mechanical, petrological, and rheological domains. Furthermore, a subduction zone exhibits features on multiple size scales ranging from hundreds of kilometers to the size of a couple of football fields as is evident in Fig. 1. In order to accurately model this phenomenon in a time-efficient manner, we have used a marker method over an Eulerian grid in order to reduce the size of the general matrix solved at each timestep while simultaneously retaining small-scale detail in the composition and temperature fields at much higher resolution than the grid used for resolving temperature and velocity fields. These details are produced mainly as a result of the rapid mechanical mixing of different rocks [2,3] during subduction.

2. Description of model

Our modeling scheme couples an Eulerian finite-difference method with a Lagrangian marker-in-cell approach in order to solve a set of equations that describe the driving forces in subduction. Eq. (1) shows the Stokes equations for creeping flow without an inertial term. This relies on the relationship between stress and strain-rate, where η represents the viscosity, which depends on temperature (T), pressure (P), chemical composition (C), degree of melting (M) and strain-rate ($\dot{\varepsilon}$). The buoyant force in Eq. (1) is dependent on temperature, pressure, composition and degree of melting. Conservation of mass is enforced through the incompressible continuity equation, Eq. (2), where we keep

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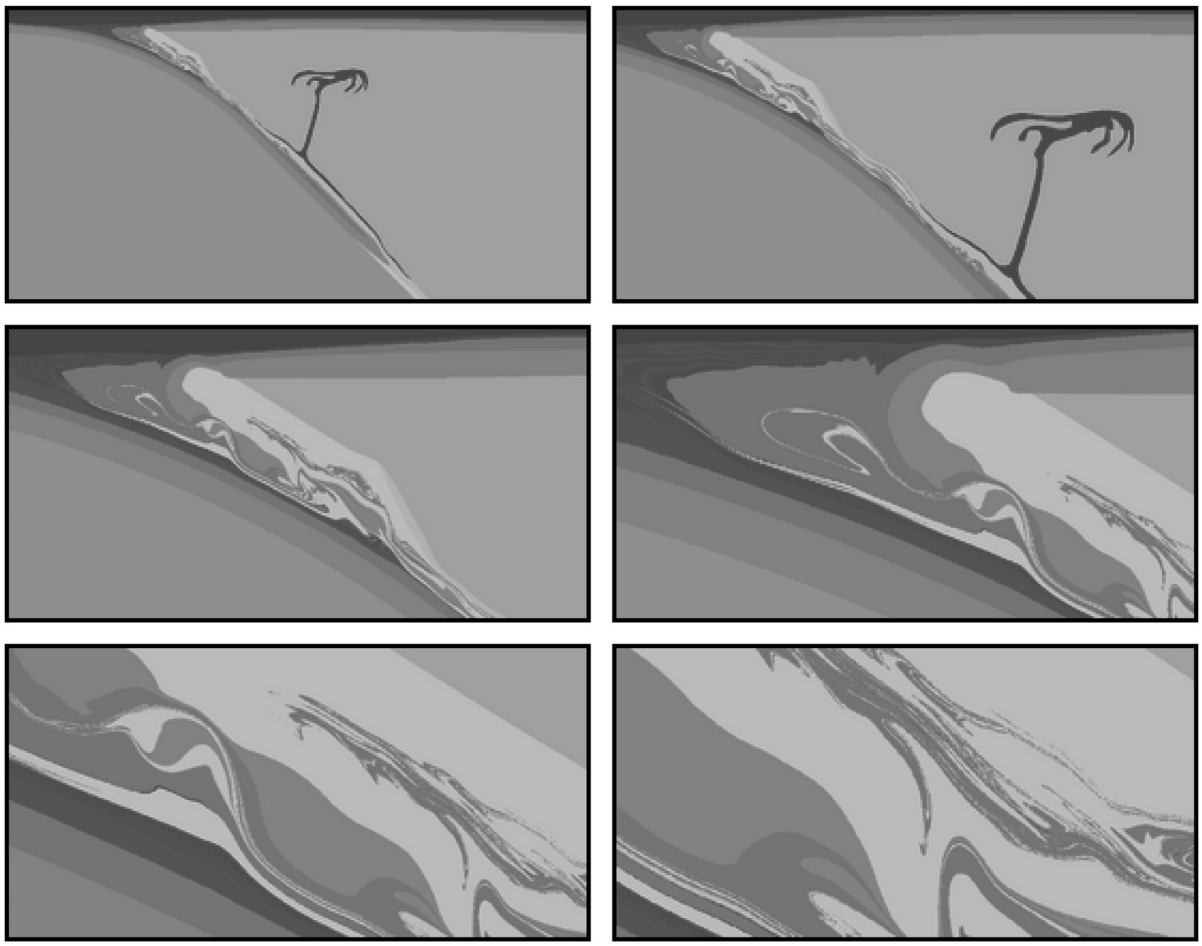

Fig. 1. This figure illustrates the multi-scale nature of our data. Starting from the upper left, we have a full frame emphasizing features on the order of 100 km. Next is what we call B-zoom, with ¼ of the original data displayed. On the second row are C-zoom (1/16 of a frame), and D-zoom (1/64 frame). In these images, the mechanical mixing under the accretionary wedge is visible. On the bottom row are E and F-zoom (1/256 and 1/1024 of one frame, respectively). In these images, fine-scale structure on the order of 10 m becomes apparent and microscale fluid dynamics can be studied.

density constant. This is the Boussinesq approximation and is generally accepted in mantle convection codes. Our temperature calculation is performed in the Lagrangian frame of reference, and we use the extended Boussinesq approximation to account for radioactive, adiabatic and viscous heating contributions. The temperature equation, Eq. (3), is nonlinear in T due to variable thermal conductivity of the multiple components.

$$\frac{\partial \sigma_{ij}}{\partial x_j} = \frac{\partial P}{\partial x_i} - \rho(P,T,C,M)g_i \tag{1}$$

$$\sigma_{ij} = 2\eta(P,T,C,M,\dot{\varepsilon})\dot{\varepsilon}_{ij},\ \dot{\varepsilon}_{ij} = \frac{1}{2}\left(\frac{\partial \nu_i}{\partial x_i} + \frac{\partial \nu_i}{\partial x_i}\right)$$

$$\frac{\partial \nu_i}{\partial x_i} = 0 \tag{2}$$

$$\rho C_p\left(\frac{DT}{Dt}\right) = \frac{\partial q_i}{\partial x_i} + H(C)_{rad} + T\alpha\rho\nu_i g_i + \sigma_{ij}\varepsilon_{ij} \tag{3}$$

$$q_i = k(T,P,C) \times \left(\frac{\partial T}{\partial x_i}\right)$$

We use a relatively simple set of conditions for our oceanic subduction setting (Fig. 2) in which an oceanic slab of given age subducts under an overriding plate with an initially prescribed thermal structure. The initial position of the subduction zone is defined using an 6 km thick hydrated peridotite layer which is spontaneously substituted by subducted crustal rocks and hydrated mantle material once subduction begins. The boundary

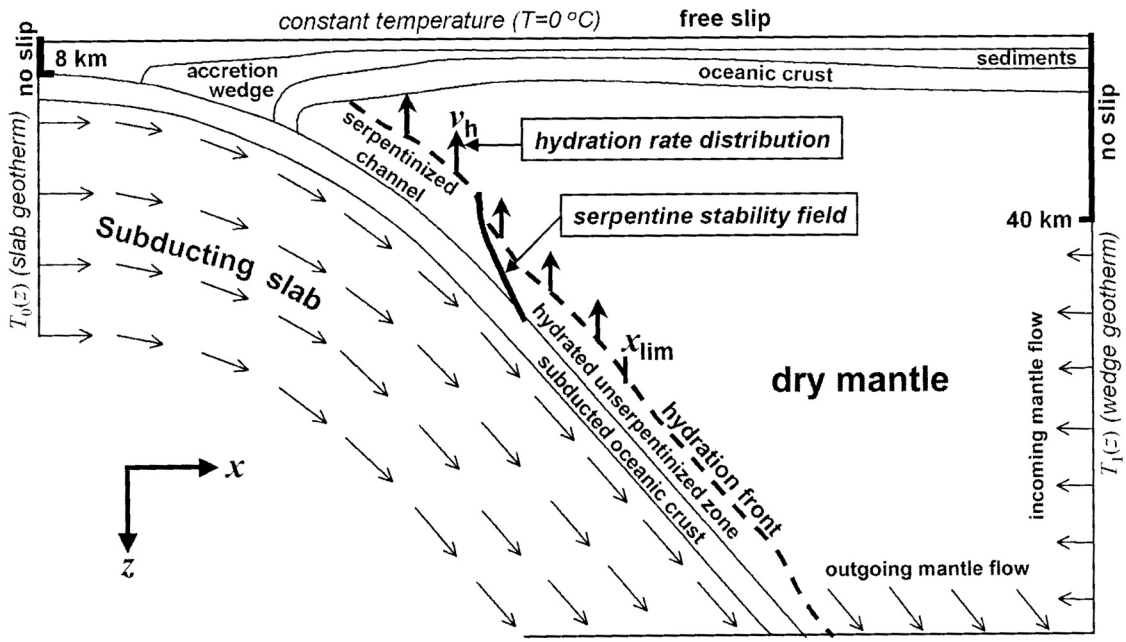

Fig. 2. Numerical model of subduction used for our 2-D numerical experiments [7]. Kinematic boundary conditions with a uniform 8 cm/a subduction rate are imposed. Initial temperature distribution T0(z) in the subducting plate is defined by 90 Myr old oceanic geotherm. Initial temperature distribution T1(z) in the overriding plate corresponds to the equilibrium thermal profile with 1350°C at 32 km depth. The initial structure of the oceanic crust (top to bottom): sedimentary rocks = 1 km, basaltic layer = 2 km, gabbroic layer = 5 km. The substantive hydration rate of the mantle wedge, vh, depends on the horizontal coordinate, x.

conditions of the simulation are based on the corner flow model [4]. To account for the flux of material across boundaries, the simulation recycles and adds markers as necessary. This causes a gradual increase of the number of markers through time and also places more markers above the subducting slab where greater resolution is needed.

3. Visualization

The primary challenges in visualizing a multiaspect simulation with one billion tracers are utilizing a relatively low-resolution display device to display extremely high-resolution data in a scientifically valuable way, achieving interactive speeds with massive data files, and effectively presenting multiple fields simultaneously. We have addressed these challenges through both large-scale visualization using a display wall and through a web-based solution that allows the user of a typical desktop computer to interact with an extremely large, remotely stored two-dimensional dataset.

The prospect of displaying an image comprised of one billion pixels is daunting at best. Typical wall-sized display devices consist of several panels of 1.3 million pixels each. The display wall that we have employed (The LCSE Powerwall, http://www.lcse.umn.edu) consists of ten panels in a 5 by 2 arrangement yielding 14 megapixels. Other display walls are on this order as well. In the workstation arena, several recent display devices feature 8–12 million pixels. However, all of these solutions are at least two orders of magnitude too small for our applications. Our solution is to downsample the original data or divide it into regions of interest in such a way as to allow easy exploration and manipulation.

Display walls are not yet commonplace or standardized and therefore the display wall is only a solution for visualization at a particular location, particularly when datasets are on the order of one terabyte, making transfer over the internet prohibitively slow. In order to fill this gap and provide remote data access to collaborators around the globe, we have created a new web-based data interface known as WEB-IS4 (http://webis.msi.umn.edu/~max/webis4/). This system allows a user to zoom in to a data set of arbitrary size with multiple fields, dynamically apply color maps to the data to bring out salient features, and can return dynamically calculated statistics concerning the region of interest. Using a sample 3 GB dataset from our simulation, WEB-IS4 provides these features with a response time of about 0.25 s, allowing true interactivity.

The WEB-IS4 interface is built on a client/server paradigm where the client is assumed to have little processing power, storage, or RAM. Our client is a simple Javascript and HTML web interface that is compatible with any modern web browser. All communication with the server takes place using traditional HTML forms for maximum compatibility and simplicity. The backend is a set of custom C programs that are executed by the Apache web server using Perl Hypertext Preprocesssor (PHP).

WEB-IS4 requires that data be reprocessed in advance. We begin with a large dataset with resolution on the order of 40k $\times$ 10k pixels. Our software creates mipmaps at lower resolutions using either mode-averaging or mean-averaging for discrete or continuous data, respectively. Mipmaps at many varying resolutions are created so that read time will be minimized during retrieval. Mipmaps are then stored in a data file in hierarchical order, so that the lowest resolution mipmap is at the 'top' and the original dataset at the 'bottom' of the hierarchy.

The WEB-IS4 backend can create TIFF format images of any region of interest from hierarchical data in 0.1–0.25 s. This speed varies only slightly with varying zoom levels and includes time spent applying a colormap to the data, resizing the retrieved data to fit the client's web browser using a bicubic method, and writing the final image to disk. A previous version of this software (Rudolph et al. [5]) without hierarchical data formats would take as long as 75 seconds just to read a data file into memory for a broad region of interest.

4. Conclusions

Our visualization methods using hierarchical data formats are promising advances in 2D visualization. In the near future, these methods will make dynamically-rendered zoomable video on display walls feasible. Our methods will also be adapted for 3D visualization and will make interactive exploration of extremely high resolution 3D data a possibility. The WEB-IS4 interface and its siblings (Wang et el. [6]) have permitted us to collaborate with scientists around the world and this type of interface shows a great deal of promise for sharing data in many disciplines.

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