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Efficient algorithms for finding sills in digital topographic maps

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Abstract

In stratified geophysical flows, the energetically optimal exchange of dense fluid across a topographic barrier generally takes place at the deepest unblocked connection, which is typically a saddle point (sill). The flow at or near a sill is often hydraulically controlled, in which case the sill is called a controlling sill. Oceanographic examples include overflows of newly formed dense water at high latitudes as well as sills in channels connecting major ocean basins, such as the Strait of Gibraltar. Controlling sills are usually associated with strong flows, making them ideal sites for monitoring transport and hydrographic variability. The locations and depths of controlling sills also provide strong constraints for the downstream hydrographic properties below sill depth. Here, two algorithms for finding sills in digital topographic maps are presented. The first approximates the sill height to arbitrary precision in $O(k)$ steps, where k is the number of data points in the map. The second algorithm, which requires $O(k \log k)$ steps, additionally returns the sill location. Several tests carried out with realistic problems from physical oceanography reveal that the second algorithm runs faster in practice, even though its worst case behavior is worse.

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1. Introduction

Inspection of any large-scale bathymetric map of the ocean (e.g. Fig. 1) reveals that the seafloor is characterized by deep basins separated by shallower topography. For example, the Mediterranean is separated from the North Atlantic by the African and European continents, with the Strait of Gibraltar providing the sole pathway for exchange of water (Fig. 1). Similarly, the deep basins of the western and eastern Atlantic are separated by the Mid-Atlantic Ridge (MAR). In regions of complex topography, such as on the MAR, the separation of the seafloor into individual basins occurs on comparatively small scales (e.g. Fig. 2).

The deepest point along a topographic barrier separating two deeper regions is usually a saddle point, and is called a sill. In order to answer a variety of oceanographic questions the locations

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and depths of the sills connecting deep basins must be determined. For example, in the absence of deep convection, the bottom-water properties in a deep basin are limited by the properties of the densest inflowing water (e.g. Saunders and Francis, 1985). In case of multiple possible pathways between two regions, the densest inflow tends to take place across the deepest sill, where the flow is often hydraulically controlled (e.g. Whitehead, 1998). Therefore, the shallowest sill in the deepest passage between two basins is called the controlling sill (CS). Because of its controlling aspect, a CS is often the ideal location for monitoring transport and hydrographic change (e.g. Hogg and Zenk, 1997).

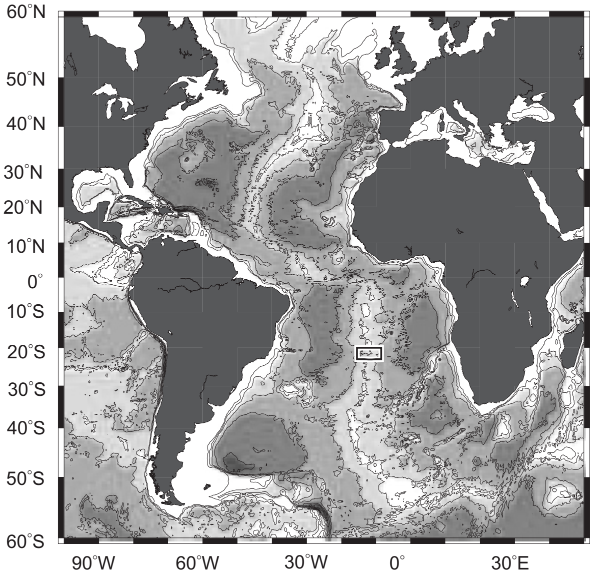

Fig. 1. Topography of Atlantic Ocean, from Smith and Sandwell (1997) global data set. Contour interval is 1000 m, shading increases with depth. Box centered near 20°S, 10°W indicates location of Rio de Janeiro Fracture Zone (Fig. 2).

As an example, consider the southern MAR between 20°S and 23°S (Fig. 2): in their analysis of data from the WOCE A14 section along 9°W, Mercier et al. (2000) describe signatures of western-basin water in the eastern South Atlantic near 22°S. Because of its proximity, they infer that the Rio de Janeiro Fracture Zone is the most likely pathway for deep-water exchange across the MAR in this region. Visual inspection of the regional topography indicates several sills with similar saddle depths (labeled "X", "Y", "Z", and "C" in the figure). Traditionally, sill locations and depths are estimated visually from bathymetric charts. In addition to being tedious, the visual method is prone to uncertainties and errors. Computers, on the other hand, are ideally suited for this task, because topographic data are usually available as digital $\langle x, y, z\rangle$ grids (digital elevation models, or DEMs). The number of data points in DEMs and, consequently, the number of possible pathways between two given locations can be large; the near-global topography of Smith and Sandwell (1997), for example, consists of nearly 7×10^7 elevation data. (Since the space requirement of a DEM grows quadratically with resolution, future data sets are expected to be much larger than that.) Therefore, it is important that sill-finding algorithms are efficient in terms of CPU and memory requirements.

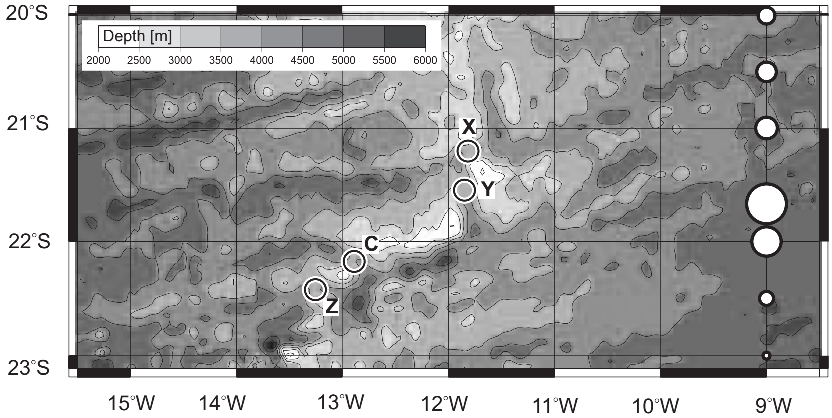

Fig. 2. Topography near Rio de Janeiro Fracture Zone on MAR, from Smith and Sandwell (1997) global data set. Diameters of WOCE A14 station symbols along 9°W are proportional to mean oxygen concentration below 3000 m, with high values near 22°S indicating western-basin water that has crossed the ridge (Mercier et al., 2000). Locations of four sills in deep passages across ridge are circled and labeled; sill depths are 3360 m (X), 3365 m (Y), 3435 m (Z), and 3460 m (C).

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