Lattice-Automaton Modelling of Bioturbation and Benthic Activity

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LONG-TERM GOALS

The long-term goal is a quantitative and mechanistic understanding of the relationship between infaunal ecology, in the form of animal actions and rates, and the consequent modification of sediments, including the creation and destruction of heterogeneities and the modes and rates of sediment component mixing.

OBJECTIVES

The development of a model-computer code, i.e., the lattice-automaton model, that embraces the discrete nature of sediments and organisms, rather than averaging it away, and that utilizes biologically relevant parameters, such as animal sizes, population density, feeding and locomotion rates, and probabilities for observed behaviour(s), to drive the model and produce predictions about sediment composition and fabric.

APPROACH

My approach is the direct modelling of organism-sediment interactions via a new type of model. Biologically active sediment is represented on a computer as a regular lattice of quasi-particles with individually assigned chemical, biological or physical properties. Model benthic organisms are introduced in the form of automatons, i.e. programmable entities that are capable of moving through the particle lattice by displacing or ingesting-defecating particles. Each automaton obeys a set of rules, both deterministic and stochastic, designed to mimic real organism behavior, with different types of organisms having different sets of rules. The acronym for the model is LABS.

This project involves myself, two post-doctoral fellows, i.e., Dr. Filip Meysman (NIOO, The Netherlands) and Dr. Katherine Huang (Dalhousie), and a Ph.D. graduate student, Daniel Reed.

WORK COMPLETED

Work in this fiscal year centered on two main activities: firstly, recoding of the program into a more-coherent object-oriented form and secondly, investigation of short-lived and short-transient tracers.

Dr. K. Huang, who holds a Master's degree in Computer Science and a PhD in Biology, is leading the effort to recode our lattice-automaton program. This is absolutely necessary as we have found that implementing new organisms (other than small deposit-feeding worms) is extremely difficult and plagued by odd un-anticipated behaviors that are code generated, not rule generated. She has completed and in-depth analysis of the code and completed the new structure of the code, but line-by-line coding still needs to be completed. A larger ecology awaits the success of this effort.

In the meantime Dan Reed and Dr. Filip Meysman have been investigating the behavior of short-lived and short-transient tracers in the “old version” of the model. Two papers have resulted from this work, Meysman et al. (2003) and Meysman et al. (in press), and D. Reed is currently working on a third paper. In addition, Boudreau has integrated the findings of this project to produce a new review paper on mixing in sediments, i.e., Boudreau (submitted).

RESULTS

The prevalent model for biological mixing of sediments is biodiffusion. It’s used to model everything, and it is not clear that such a universal application is valid, both specifically and generally. Thus, our scientific efforts have focused on short-lived and short-transient tracers because these types of tracers are the mostly likely candidates to violate the assumptions of the biodiffusion model, if violations do occur.

We have been running simulations of various radio-active tracers, i.e., ^{234}Th (half-life = 24.1 d), ^{7}Be (53.6 d), ^{228}Th (1.9 yr), ^{210}Pb (22.3 yr) and ^{32}Si (101 yr), to steady state with varying numbers of organisms. Steady-state occurs in 5 half-lives of the longest lived isotope, i.e., about 500 years for these isotopes. A 50-year time series of D_B values calculated after 500 years from the model-generated depth profiles of each isotope is given in Figs 1. All isotopes are subject to the same degree of mixing, i.e., there is no selection in these simulations. Yet, the D_Bs are very different for the short-lived isotopes, compared to the long-lived ones, and are highly variable with time, even if “steady state” should theoretically prevail.

The time variability of the short-lived isotopes indicates that they violate the “temporal” condition for biodiffusion, i.e., they decay significantly between mixing events. This conclusion was also reacted in Meysman et al. (2003). The larger values of D_B for the short-lived isotopes indicates that their mixing is on a spatial scale that is larger than expected by diffusion. That is to say, because all isotopes are mixed with the same intensity, we would expect the e-folding depth of the short-lived isotopes (see Fig. 2) to scale to the e-folding distance of the long-lived isotopes by the ratio of their half-lives. This is not the case; the short-lived isotopes penetrate much deeper than expected, as much as an order of magnitude deeper.

We have not established an exclusive explanation for the deeper penetration of the short-lived isotopes. Two cause are candidates: 1) the finite mixing distance of the organisms, and 2) tumbling down burrows near the surface. Neither process causes long-lived isotopes to deviate from biodiffusive behavior, but both can serious affect short-lived isotopes. We continue to try to sort out the contribution from both processes.

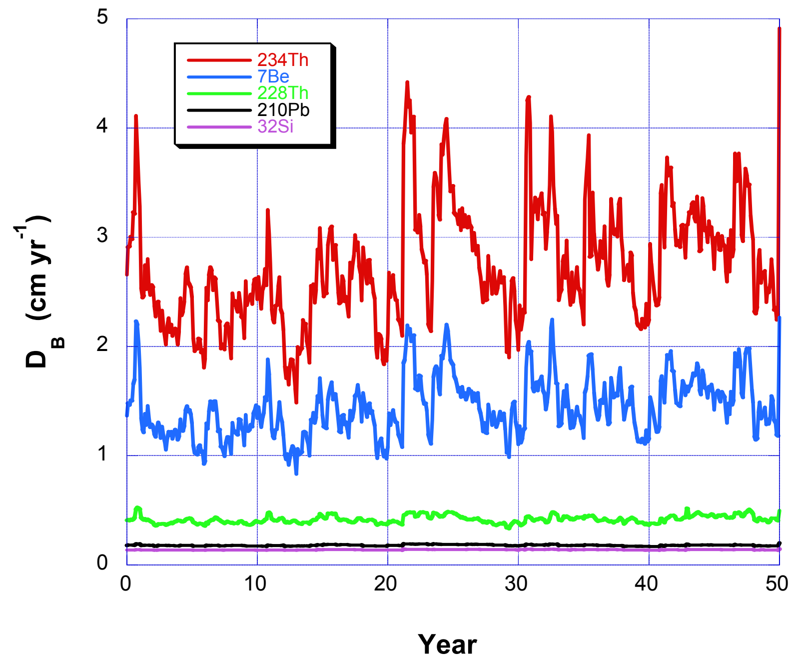

Figure 1. Time series of the D_B values calculated for short and long-lived isotopes after the model should have reached a 'Steady State" (500 years into the simulation). All isotopes are subject to the same amount of mixing and there is no selectivity. All isotopes are supplied by constant input from the water column.

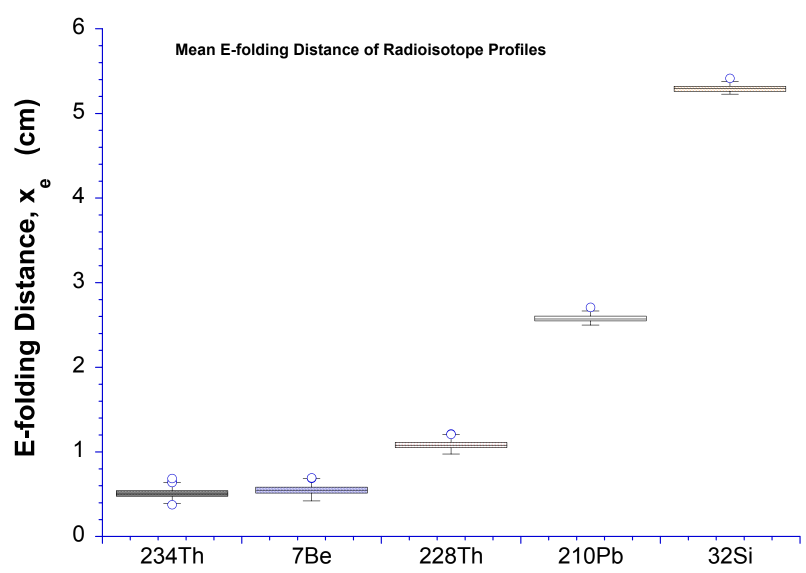

Figure 2. Calculated mean e-folding depths (penetration distances) of short-lived and lon-lived isotopes in a model sediment.

We have also continued to examine short-transient tracers, which are stable tracers with time dependent inputs. Boudreau et al. (2001) report and early set of results from the LABS model, but we now know these to be erroneous. The error was generated by nor accounting for all possible movement of particles that "wrap around", i.e., go from one side of the model to the other. The error was not seen as an error because the results were in accord with G.I. Taylor's predictions for early time diffusion, i.e., concave up on a time versus "mean-squared-displacement" plot. Our corrected results are shown in Fig. 3. This shows that there is curvature, i.e., time dependence in D_B, but that the curvature is concave down. This makes more physical sense, as mixing cause larger than expected displacements at early time (as seen in nature), and the long-term behavior is diffusive (linear). Much more needs to be done in this area of research.

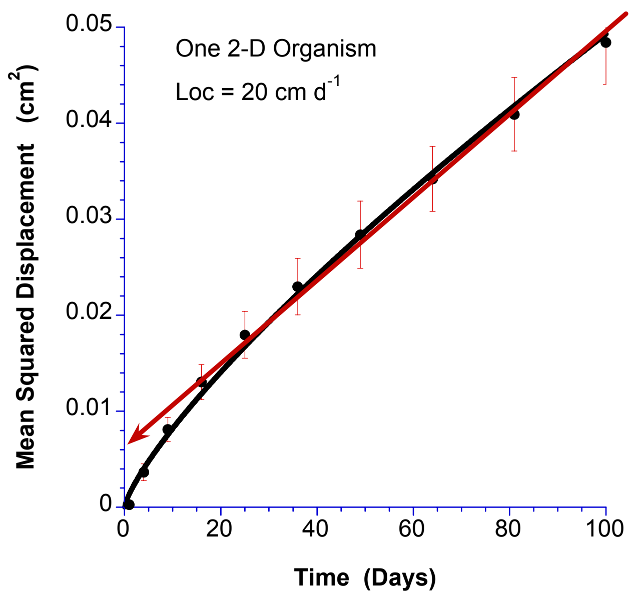

Figure 3. Time change of the mean-squared displacement of a transient stable tracer in the LABS model. Pure biodiffusion should plot linearly. The early curvature is due to non-local (large spatial) displacements of the particles .

IMPACT/APPLICATIONS

LABS and our related analyses have the potential to alter our understanding of mixing of sediments and to make **predictions** that can be tested.

Short-lived isotopes are commonly used by biologists and geochemists to estimate mixing in sediments; our results seem to indicate that these isotopes cannot be used in this way. This has important implications for current and past research.

TRANSITIONS

Peter Jumars at the Darling Center are continuing their collaborations. B. Boudreau visited the darling Center in June to confer on this research, and Boudreau now serves on one of Jumars's students has visited the Dalhousie lab (Kelly Dorgan). Boudreau will now serve on Kelly's PhD committee.

RELATED PROJECTS

We have been amazed to find that our bubble work (ONR N00014-99-1-0063) has implications for our mixing work. Working with Peter Jumars and Kelly Dorgan, we have found that some bioturbators move in sediments by cracking the sediment open, rather than displacing sediments. We need to take this into account in LABS.

PUBLICATIONS

Boudreau, B.P., Choi, J. and François-Carcaillet, F. (2001) Diffusion in a lattice-automaton model of bioturbation by small deposit feeders. Journal of Marine Research 59, 749-768. [refereed, published]

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Meysman, F.J.R., Boudreau, B.P., and Middelburg, J.J. (in press) Why does biological mixing resemble Fickian diffusion? Journal of Marine Research. [refereed, in press]