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Global compilation of surface mixed layer parameters (sedimentation rate, bioturbation depth, mixing intensity) from marine environments: The SMLBase v1.0

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Introduction

In the surface mixed layer (SML) of a sediment body, sedimentary particles such as skeletal remains are mixed and moved by a variety of processes. In its simplest form, their movement can be described by a burial component (advection, specified by the sedimentation rate), and a mixing component (diffusion, specified by mixing intensity and mixing depth; Guinasso and Schink 1975). The interaction of these two components plays an important role in different geoscientific disciplines, as it influences how information recorded by sedimentary particles enters the geohistorical record. After transiting the SML, younger particles can be buried below older particles (e.g., Dominguez et al., 2016). The resulting age inversions contradict the paradigm of age-depth modeling that the age of sedimentary particles strictly increases with their burial depth (Haslett and Parnell 2008). The stratigraphic offset of particles of identical age can be more than a meter (Tomašových et al., 2018), generating age inversions when individual particles are dated to construct age-depth models. Similarly, particles found at the same stratigraphic position can have ages that differ by millennia. This reduces the temporal resolution of stratigraphic time series and limits the fastest ecological change recognizable in the fossil record (Kidwell et al., 1991). Understanding how sedimentary particles are mixed and buried in the SML is thus crucial to the proper interpretation of geohistorical data.

Multiple databases of surface sediment parameters that describe individual aspects of the surface mixed layer have been published in the past. This includes bioturbation depth and mixing coefficients in Teal et al. (2008), bioturbation intensity by Solan et al. (2019), and sedimentation rate and biodiffusion coefficient by Middelburg et al. (1997). However, these databases record individual SML parameters from different sampling locations. As a result, they don’t allow simulating the SML.

Here, I present a database of empirically informed models of the SML in marine environments that captures the dependencies between mixing and burial on a global scale.

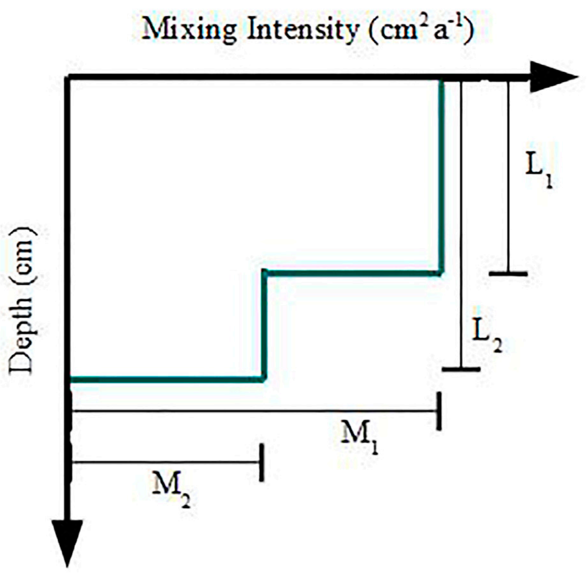

FIGURE 1
Parametrisation of the surface mixed layer (SML).

The models have been compiled from published literature and curated. Each model provides a description of the burial and mixing processes at a well-defined sampling-site. The models are described as box models with parameters estimated from tracer experiments, and can be used directly to inform simulations of the surface mixed layer. SMLbase v. 1.0 is available for download at zenodo under https://doi.org/10.5281/zenodo.6509267 (Hohmann 2022).

Data compilation and selection

A literature search on Google Scholar and Web of Science with for the keywords “Sedimentation”, “Bioturbation”, and “Biodiffusion” was used to identify relevant publications. From these publications, those that recorded marine sampling sites where data on sedimentation rate, bioturbation depth, and biodiffusion coefficients was available, were selected. From this selection, the following were excluded:

1. Sites where bioturbation depth was determined by tracer penetration depth (e.g., Caroll et al., 2008). In the box models used, bioturbation depth parameters should reflect a change in mixing intensity (Figure 1). Tracers with longer half-lives persist in the sediment for longer and thus have larger penetration depths, demonstrating that penetration depth does not reflect a change in mixing intensity.
2. Sites where mixing coefficients did not drop to 0 at the bottom of the core (e.g., Legeleux et al., 1994). Sedimentary particles reaching depths where mixing is zero will be absorbed in the deep sediment layer, and enter the geohistorical record. At sampling locations where mixing does not drop to zero, particles can hypothetically resurface due to mixing, making these sites unsuitable for models that examine how geohistorical information is fixed in the stratigraphic record.
3. Sites where mixing values were larger than 10^5 (e.g. Edelman-Furstenberg et al., 2020). If mixing is rapid relative to tracer half-life, tracer concentration in the SML will be constant, leading high estimated values of biodiffusion with large uncertainties (effectively transitioning from the model by DeMaster and Cochran (1982) to the model by Erlenkeuser (1980)). Sites with very large diffusion coefficients should thus be considered completely homogenized on the timescale of the used tracer, with no reliable estimate of mixing intensity available.

For tracer records that were analysed multiple times (e.g. volcanoclastics from Glass et al. (1973), analysed by both Guinasso and Schink (1975) and Officer and Lynch (1983)), the most recent analysis was used. When estimates based on tracers with different half lives are given for the same sampling site, the set of estimates that has the most consistent half life is listed in the data base to circumvent biases that arise from the scaling of mixing and sedimentation rate with the time scale of observation (Sadler 1981; Smith et al., 1993), see also “Database Characteristics”. Sediment mass accumulation rates (e.g., in g cm^{-2} a^{-1}) were converted into sedimentation rates (in cm a^{-1}) using the sediment density measured at the sampling site. A total of forty-seven publications published between 1973 and 2020 met these criteria and contributed data to the database (Glass, 1969; Nozaki et al., 1977; Peng et al., 1979; Cochran and Krishnaswami, 1980; Ruddiman et al., 1980; DeVito, 1981; Carpenter et al., 1982; Nittrouer et al., 1984; Li et al., 1985; Zuo et al., 1991; Buffoni et al., 1992; Radakovitch, 1995; Van Weering and de Stigter, 1995; Soetaert et al., 1996; Middelburg et al., 1997; Zuo et al., 1997; Abassi, 1998; Dellapenna et al., 1998; Alperin et al., 1999; Radakovitch et al., 1999; Sanchez-Cabeza et al., 1999; Smith and Schafer, 1999; Smoak and Patchineelam, 1999; Nie et al., 2001; Alperin et al., 2002; Masqué et al., 2002; Masqué et al., 2003; Radakovitch et al., 2003; Muñoz et al., 2004; Miralles et al., 2005; Niggemann, 2005; Niggemann and Schubert, 2006; Carroll et al., 2008; Cox et al., 2008; Mouret et al., 2009; García et al., 2010; Maiti et al., 2010; Carvalho et al., 2011; Stolze, 2016; Edelman-Furstenberg et al., 2020).

Database structure

Each sampling site in the database is assigned a unique site Id. Each site id has one box model assigned to it, a list of additional information on sampling sites (water depth in m, sampling year and month, core name, and sampling site coordinates in decimal degrees) and bibliographic

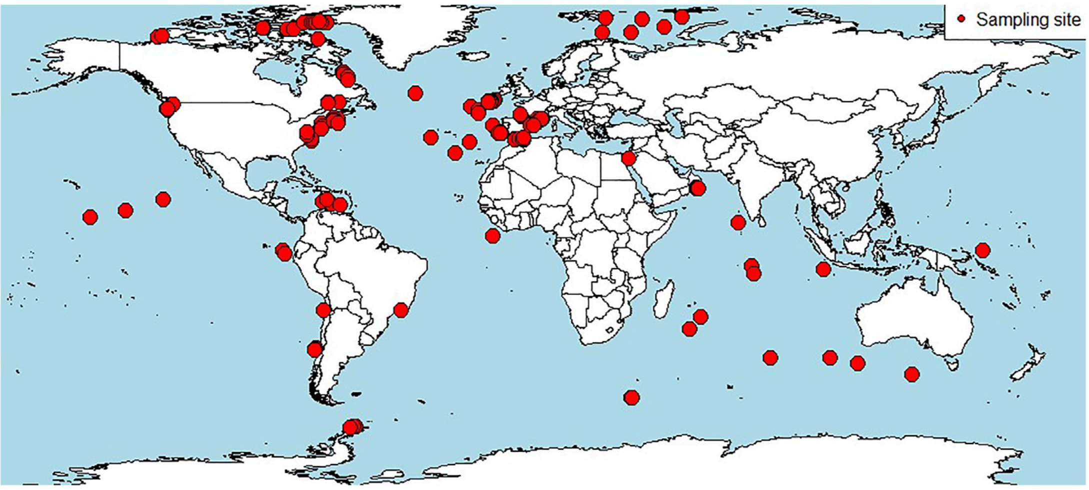

FIGURE 2
Localities of sampling sites in the database.

information on all publications that contributed to the database entry.

Parametrisation of the surface mixed layer

A two box model is used to describe the surface sediment layer in the database (cf. Santschi et al., 1980). A box model consists of sedimentation rate S (in cm a^{-1}), one or two mixing intensities M_1, M_2 (in cm^2 a^{-1}), and one or two bioturbation depths L_1, L_2 (in cm). The first box describes the mixing intensity M_1 between the sediment surface and sediment depth L_1, the second box describes the mixing intensity M_2 between the sediment depths L_1 and L_2. Below L_2, mixing intensity drops to 0 (Figure 1). This parametrization of the surface mixed layer is compatible with all empirical data extracted from the compiled literature, and matches the model assumptions made by methods that estimate surface sediment parameters from tracer distributions. To accommodate for models with only one box (M_2 and L_2 not given) that report uncertainties in the parameters M_1 and L_2 (e.g. Carpenter et al., 1985), values for M_1^{min}, M_1^{max}, L_1^{min}, and L_1^{max} are also included in the database. For a description of the methods used to estimate the parameters in the database please see the original publications where the parameter values were estimated.

Database Characteristics

The database contains a total of 296 box models. Only 18 box models (approx. 6%) describe the SML using a two-box model and thus document depth-dependent mixing within the SML. The geographic distribution of sampling sites is focused on the northern hemisphere, with the majority of sampling sites being from North America and Europe (Figure 2). More than 50% of sampling sites are located between 40 and 50° latitude north (Supplementary Figure S1). Sampling sites range from intertidal to deep sea environments with a range of 0–5,430 m water depth. Median and mean water depth of sampling sites are 400 m and 997 m respectively. The majority of sampling sites is between 100 and 1,000 m water depth (Supplementary Figure S2). There are a number of observation biases in the database that are a direct reflection of where studies on the SML are performed, and how SML parameters are estimated.

There is a strong geographic bias towards Europe and North America in the literature. Even within these well sampled regions, data availability is often determined by large studies and spatially heterogeneous. As an example, the western Mediterranean is well represented due to the extensive study of the Rhone delta, whereas no data from the eastern Mediterranean is available. Outside of Europe and North America, data is mostly available in areas with distinct oceanographic properties, e.g., upwelling (Niggemann and Schubert, 2006) or oxygen minimum zones (Smith et al., 2000), or because of the presence of hazardous materials due to radioactive waste disposal (Kershaw 1985) or nuclear weapons incidents (Smith et al., 1994). As a result of the geographic biases of the available literature, the spatial and environmental coverage of the database is patchy.

The tracers used to estimate SML parameters are summarized in Supplementary Table S1. ^{210}Pb is the most common tracer in the database, providing more than 75% of SML parameters. Joint analyses of multiple tracers (e.g., ^{210}Pb and ^{137}Cs) provide for a total of 10.5% of sedimentation rates, mixing intensities and bioturbation depths. 84.5% of parameters are estimated based on steady state conditions. Only 5% of box model parameters are based on single pulse or variable input tracers, while 10.4% are based on a combination of steady state and single pulse/variable input tracers. 88.9% of the box models use the same combination of tracers to estimate all box model parameters.

Sedimentation rates and mixing coefficients decrease as the time scale of observation increases (Sadler 1981; Smith et al., 1993). For tracer experiments, the time scale of observation is limited by the tracer half life, and is commonly stated to be around four times tracer half life (e.g., Masqué et al., 2003). Because ^{210}Pb is the most common tracer in the available literature, most studies examine the SML on the time scale of one century. Data on environments where 1) burial and mixing is much faster or 2) mixing and burial is much slower than centennial are thus most likely under-represented in literature and the database.

Basic information on sampling sites is not consistently reported in the literature, e.g. for 21.3% (n=63) of sampling sites no exact measurements of water depth were published, and for 47% (n=140) of sampling sites, no exact coordinates were given. To accommodate for this, possible ranges for water depths and latitude and longitude were extracted from figures and are reported in the database.

Summary

I have introduced the SMLBase, a curated global compilation of models of the marine surface mixed layer. Each box model describes the mixing (diffusion) and burial (advection) of sedimentary particles and their dependencies at a sampling site. Box model parameters in the database were extracted from the published literature and are based on tracer experiments. The database provides a comprehensive assessment of the available data on the surface mixed layer, including the spatial and environmental variability documented in the literature. It can directly be used to inform simulations of the surface mixed layer that examine how information enters the geohistorical record.

Data availability statement

The SMLbase version 1.0 is deposited at zenodo and available *via* the doi https://doi.org/10.5281/zenodo.6509267 (Hohmann 2022). It consists of two files:

- *SMLBase.csv:* File containing the database information (box model id, box model parameters, water depth and coordinates of sampling sites, sampling date, short bibliographical information of publications that contributed data to the database)
- *SMLBaseDataSheet.pdf*: File describing the individual fields of the database in detail and providing full bibliographical information on all publications that contributed to the database.

All publications that contributed data to the database are also listed under “References” in this article. The database will be updated regularly to include newly published data and data from sites that were previously not covered.

Author contributions

The author confirms being the sole contributor of this work and has approved it for publication.

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Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher’s note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2022.1013174/full#supplementary-material

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