Biogeosciences
Discussions

Open Access

Repercussions of differential settling on sediment assemblages and multi-proxy palaeo-reconstructions

A. G. M. Caromel, D. N. Schmidt, and J. C. Phillips

School of Earth Sciences, Wills Memorial Building, Queens Road, Bristol, BS8 1RJ, UK

Correspondence to: A. G. M. Caromel (aude.caromel@bristol.ac.uk)

BGD

10, 6763–6781, 2013

Repercussions of differential settling

A. G. M. Caromel et al.

Title Page

Abstract	Introduction
Conclusions	References
Tables	Figures

|◄ | ►|
◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Abstract

Microfossils preserved in marine sediments are at the centre of numerous proxies for palaeoenvironmental reconstructions. Their precision is based on the assumption that they accurately represent the overlying watercolumn properties and faunas. In this paper, we assess the possibility of a pre-depositional bias in sediment assemblages caused by horizontal drift, due to differential settling velocities of sedimenting particles based on their shape, size and density. We calculate the lateral transport undergone by planktic foraminifera and a range of other proxy carriers in several regions with high current velocities. Lateral transport of different planktic foraminiferal species is minimal due to high settling velocities; no significant shape- or size-dependent sorting occurs before reaching the sediment, making planktic foraminiferal ideal proxy carriers. Diatoms, radiolaria and faecal pellets can be transported up to 500 km in some areas. This transport bias suggests that sediment assemblages could contain different proportions of local and imported particles, decreasing the precision of proxies based on these groups and the accuracy of the temperature reconstruction. For example in the Agulhas current, transport can lead to differences of up to 2°C in temperature reconstructions between different proxies. For future palaeoenvironmental reconstructions, further sediment-trapping studies and multi-proxy analyses should attempt to quantify the margin of error associated with particle transport.

1   Introduction

Reconstructing the physical and chemical variables of past marine environments relies on indirect proxies found in the marine sedimentary record. These proxies are usually based on the abundance, morphology and chemistry of organisms whose skeletons preserve in ocean-floor sediments, such as foraminifera, radiolaria and diatoms (Henderson, 2002). Geochemical reconstructions make use of the differential incorporation of a wide range of isotopes and elements into shells, whether actively selected for by

the organisms or passively reflecting the state of the surrounding watercolumn, as well as the ratios of organic molecules produced in metabolic processes modulated by the environment (Henderson, 2002). The relative abundance and morphology of microfossil species in sediment assemblages can be analysed mathematically, for example by the establishment of transfer functions, which compare the assemblage composition to calibration datasets of faunal counts from assemblages of known environmental conditions (e.g. Chen and Prell, 1998; Kucera et al., 2005), allowing us to infer the conditions under which the organisms found in the sediment assemblages lived.

Underlying all of these proxies is the assumption that the sediment assemblage analysed is a true representation of the overlying watercolumn ecosystem and microorganism population for a given location. Whilst attention has been paid to removing potential biases in assemblage composition such as dissolution of foraminiferal and diatom species (e.g. Berger, 1970; Berger and Piper, 1972; Shemesh et al., 1989; Battarbee et al., 2005) and post-depositional reworking of sediments, via re-suspension, sorting and transport of sediments by ocean-floor currents (e.g. Berthois and Le Calvez, 1960; Thiede, 1981; Kontrovitz et al., 1978), the possibility of pre-depositional bias whilst sinking to the ocean floor is largely overlooked.

Yet, settling experiments of various organic and inorganic particles have shown that differences in size, shape and density lead to differences in settling rates between particles (McNown and Malaika, 1950; Fok-Pun and Komar, 1983; Komar and Reimers, 1978; Caromel et al., in preparation). While some of the possible influences are intuitively predictable, others are more complicated to assess. For example, greater size and density both increase the settling velocity; for particles of the same size, those with flatter morphologies have lower sinking rates than more rounded shapes (Caromel et al., in preparation). As a result, particles from different organisms, species or size fractions take varying lengths of time to reach the ocean floor and are therefore affected differently by lateral currents. In general, we would expect horizontal drift to transport particles with lower settling rates over greater distances. This could alter relative abundances of different species and size fractions of microfossils in the sediment

assemblages, thereby biasing the perceived link between organisms and their environ-
ment and hence the explanatory power of transfer functions and geochemical proxies.
The respective settling velocities of the particles, combined with the distance to the
seafloor and the strength of the lateral currents encountered, will determine the impor-
tance of any sorting bias in the sediment assemblages.

Here, we consider the potential for bias in sediment assemblages by calculating the
distance of lateral transport undergone within a fossil group and by comparing and
contrasting different proxy carriers. We use planktic foraminifera as our model group
as they are widely used as proxy carriers, and a range of other microfossil groups and
particles of organic origin to assess potential biases in multi-proxy reconstructions at
several high-velocity current locations.

2 Materials and methods

The terminal settling velocities of nine species of planktic foraminifera (Table 1) rep-
resenting a range of foraminiferal morphologies and densities were determined exper-
imentally (see Caromel et al., in preparation, for full methodology). The settling ve-
locities of dead diatoms and radiolaria, and particles of marine snow, faecal pellets
and diatom aggregates were obtained from a number of literature sources (Table 2).
Coccoliths, which are the other major biotic contributors to sediments, are thought to
undergo dissolution before reaching the sediment in the undersaturated deep water-
column, unless exported within faecal pellets (Honjo, 1976). Settling velocities were
derived for dead organisms, not taking into account any positive buoyancy from resid-
ual cytoplasm, which would lengthen the time spent in the water column.

Kucera et al. (2005) identified the Benguela Current off the south-west coast of Africa
as a region where different transfer functions produce discrepancies in sea surface
temperature reconstructions. One possible reason could be advection from the Indian
Ocean into the Benguela Current. We have therefore chosen a site in the Benguela
Current (7.2° E –19.8° N) and in the Agulhas Current (32.4° E –34.2° N) to test this

**Repercussions of
differential settling**

A. G. M. Caromel et al.

Title Page

Abstract	Introduction
Conclusions	References
Tables	Figures

|◄ |►|

◄   ►

Back   Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

hypothesis. Two further sites underlying high-velocity currents were selected, a Gulf Stream-influenced location off the coast of Florida (–75.6° E 30.6° N) and one within the Kuroshio Current along the western shore board of the Pacific (136.8° E 30° N).

The annual mean velocity depth profiles for the selected locations (Fig. 1) were extracted from a historical run (for the year 2000) of the UVic Earth System Climate Model version 2.9, which replicates broad patterns of present-day ocean circulation (Weaver et al., 2001). The UVic model couples a reduced complexity atmosphere model with a 3-D general circulation ocean model, and has a grid resolution of 3.6° (zonal) by 1.8° (meridional) with 19 unequally spaced depth levels (Weaver et al., 2001). For each depth interval, the eastwards and northwards components of the horizontal velocity were obtained and used as constant throughout the depth interval in the transport calculations. Eastwards and northwards lateral transport components over a given depth interval were calculated separately as the vector sum of the settling velocity and the horizontal current velocity. Total travel distance is the resultant of the total eastwards and northwards transport components.

3 Results and discussion

Predicting water column behaviour is notoriously difficult because of the variety of fluid motions, both organised and disorganised, that occur in the ocean and generate energy transfer and turbulence at a vast range of scales (Peters and Redondo, 1997). Hence we simplified our analysis to derive some general idea about the impact of transport on multi-proxy studies. Our model is a water column without turbulence or stratification, created by temperature and salinity differences, though both are known to influence the settling behaviour of particles. Turbulence has been shown to both accelerate and retard particle settling by resuspension (Ross, 2006) and cause accumulation (Kiorboe, 1997) and disaggregation (Alldredge et al., 1990) of particulates on different energy scales. Particles with the lowest settling velocities are more easily entrained in resuspension (McCave et al., 1995), which would increase the time spent

in the watercolumn by particles already travelling the furthest. Stratification results in increased drag on particles at density interfaces (Yick et al., 2009), contributing to accumulation of particles there (MacIntyre et al., 1995). In addition, the decreasing water density and increased water viscosity caused by decreasing temperature with depth,
5 slow down particle settling (Caromel et al., in preparation). Stratification is thus also expected to extend the settling time of particles, with the amplitude of the effect being governed by the sinking rate of the particles (Lande and Wood, 1987). The simplifications therefore leads to our estimates being minimum settling times, so calculations of horizontal transport are at least as large as we suggest.

10 ## 3.1 Influence on planktonic foraminiferal assemblages

The lateral displacement of any planktic foraminifer is smaller than 10km for all species and sites (Fig. 2). This is due to their high settling velocities, causing them to fall out of the watercolumn within two days at most. As expected, the more heavily calcified species *G. truncatulinoides*, *G. tumida* and *G. conglobatus* travel the shortest distance,
15 as their settling velocities are highest. *Orbulina universa* exhibits the greatest range of transport distances because of a wide range in settling velocities in this species, despite similar ranges in size to other species (Table 1). This wide range can be attributed to the variability in density in *O. universa* caused by resorption of the earlier chambers and variable wall thickening (Bé et al., 1973).
20 At first glance, a shape-dependent differentiation in transport is not apparent. There is significant overlap in the distances travelled for all foraminiferal species. As each foraminiferal species has their own size range (Schmidt et al., 2004) though, the distance travelled is governed by the sinking speeds over the species-specific size range. For example, a normal-sized flat *G. menardii* specimen of 950 µm is twice as big as
25 typical rounded *G. ruber* and *G. trilobus* but exhibits similar settling velocities (Table 1). Considering specimens of similar sizes across species, as happens in the narrow size fractions picked for trace elements for temperature reconstructions for example, a *G. menardii* specimen would sink half as fast as one of a rounded species (Caromel

et al., in preparation) and therefore cover twice the distance by lateral transport. Importantly, though, even with this bias in our settling experiments taken into account, the overlap in the ranges of distances travelled between all species remains, which implies that even at high-current velocities, no significant shape-dependent sorting occurs.

The specimens used in the settling experiments ranged 260–1590 μm in size, therefore under-representing smaller size fractions and biasing our results towards higher settling velocities. However, the size fraction generally used for assemblage reconstructions is greater than 150 μm and for geochemical analysis often around 300 μm (Al-Sabouni et al., 2007), therefore at the higher end of settling velocities. Extrapolating from the settling data of the species with the lowest settling velocity, *Orbulina universa*, we would expect at most a tripling of the maximum distance travelled for the smaller specimens. Even in the Agulhas current, where the current velocities are high and hence the maximum distance travelled, the smaller size fraction would reach a maximum distance of 22.5 km, which should not be sufficient to create significant sorting based on size. In addition, many of the smaller, juvenile stages of the foraminiferal population are removed from the upper watercolumn in larger aggregates and faecal pellets (Hemleben et al., 1989), leading to their export to the sediment faster than as individual tests, reducing the potential for size-dependent sorting.

The very small lateral displacement overall by all shapes and sizes should consequently not introduce a bias in the proportional representation of species and size fractions in sediment assemblages. The discrepancies produced by different calibration techniques of transfer functions in the Benguela region is therefore not likely to be caused by transport of a subset of dead foraminifera by the Agulhas current, but rather by the presence of a displaced live foraminiferal population advected into the region by a ring of Agulhas waters, diluting the local signal (Peeters et al., 2004). Corrected for dissolution and post-depositional reworking, and allowing for variable microenvironments such as the Agulhas ring, planktic foraminiferal assemblage composition can therefore be confidently used in proxies to represent the overlying water column structure in all locations, and the geochemistry of different species from the

same samples can reasonably be used to reconstruct different depths of the water column.

3.2 Influence of settling velocity on multi-proxy studies

While settling does not seem to produce a bias in foraminiferal assemblage-based transfer functions, settling velocities of other proxy carriers can range up to two orders of magnitude lower (0.00007 to 0.0048 m s^{-1}) than those of planktic foraminifera of 0.03 to 0.05 m s^{-1} (Table 2). Consequently, the scope for individual lateral displacement and consequent bias between the different groups of proxy carriers due to sorting is much greater than for foraminifera (Fig. 3). Whilst radiolaria, diatom aggregates, faecal pellets and other particulate matter such as marine snow can rival planktic foraminifera in size, their lower densities and weight result in lower sinking speeds (Takahashi and Honjo, 1983; Alldredge and Gotschalk, 1988; Yoon et al., 2001) and hence greater horizontal drift. Individual diatoms travel the furthest and have the greatest range of distance covered, attributable to their generally small size and consequent very low settling velocities (Table 2).

Overall the amount of transport undergone by diatoms found in sediment assemblages is difficult to assess, as their mode of transport, whether they are exported as individual cells, or as part of flocs or faecal pellets, influences the amount of lateral transport they experience (Fig. 3). In general, small particles are often scavenged by larger ones through turbulence and differential settling (McCave, 1984). Specially, in a bloom situation with high particle densities, mass flocculation into aggregates (Alldredge and Gotschalk, 1989) results in rapid export of diatoms directly below their production zone in surface waters (Kiorboe et al., 1994).

The low settling velocities in the different groups of proxy carriers result in potential transport of tens of kilometres to over a thousand depending on location (Fig. 3). The effect of the export of certain particle types from high-velocity locations is two-fold: firstly, the proxies based on geochemistry or assemblage composition of radiolaria, diatoms or organic signals and coccoliths derived from faecal pellets could be importing

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

a signal from a distant location compared to proxies based on foraminifera, which will record more local signals as they are transported just a few kilometres. This, in addition to post-depositional sorting, can partly explain instances where temperatures derived from co-occurring alkenones and foraminifera do not agree (Benthien and Müller, 2000; Ohkouchi et al., 2002).

Secondly, the wide range of distances travelled within particle types due to differences in current velocities means that, at different sites, assemblages will contain varying proportions of local and imported particles, diluting the local signal to varying degrees, as has been established for example for terrigenous material (Franzese et al., 2006). This implies that correcting the proxy signal for particle transport is not as straightforward as identifying the source location of the imported particles, but requires establishing how much imported and local particles each contribute to the sediment assemblage, also taking into account the proportion of the local population lacking due to exportation. In effect, the signals from smaller or lighter proxy carriers will be smeared over a greater distance and amalgamated with the other signals distributed over that area. This reduces the precision with which variables can be reconstructed for specific locations, which should be reflected in greater error ranges for measurements. In contrast, assemblages of larger and denser proxy carriers such as foraminifera will record more discrete local signals, and precision is dictated solely by the analytical methods used.

In addition to particle properties, variations in current velocity will dictate the geographical and temporal applicability of different proxies. Within the Benguela current (Fig. 3), the distance travelled by all particles in a north-north-westerly direction does not exceed 40 km. Therefore, we would expect no sorting bias in the proxy reconstructions, and sediment assemblages to predominantly reflect the overlying water column properties with minimal import. At the other tested locations, though, radiolaria and faecal pellets can be transported up to 500 km, individual diatoms over 1000 km, whilst foraminifera, marine snow and diatom aggregates travel at most 150 km (Fig. 3). These differences in transport distance result in a vastly different catchment area. For

Repercussions of differential settling

A. G. M. Caromel et al.

example, in the Agulhas current, particles travelling an intermediate distance (300 km) from the tested site are displaced south-westerly by 1.8° W in longitude and 2.4° S in latitude. In the present-day ocean, temperatures in the original site are consistently 2°C higher than in the catchment area (Locarnini et al., 2010); as a result, temperature reconstructions at this new site could potentially have a large associated error. Despite the shallow water depth of the Florida site, the Gulf Stream can carry the lightest radiolaria and other equivalent particles 2.5° in a northerly direction and 0.7° E. The Kuroshio Current sees large eastwards velocities at shallow and intermediate depths, transporting these particles 2.2° E, with a minimal northerly direction. In both of these locations, temperature profiles with depth are similar at both sites (Locarnini et al., 2010), suggesting that even with export of particles, no error would be introduced given the current temperature distributions.

However, due to changing circulation patterns and intensity over time, for example in glacial-interglacial cycles, transport and its effect on proxies will vary given changing environmental conditions. For example, during the Last Glacial Maximum, shifts in the Angola-Benguela front (Little et al., 1997) and the Kuroshio current (Ujiié et al., 2003) changed local current configuration, making the assessment of the effect of transport on these systems currently impossible due to the lack of detailed proxy reconstructions of their flow. In contrast, the Agulhas current and the Gulf Stream were weaker (Franzese et al., 2006; Lynch-Stieglitz et al., 1999; Peeters et al., 2004), implying shorter transport distances and less bias in our ability to reconstruct past environments based on biological proxies.

4 Conclusions

The high settling velocities of planktic foraminifera result in minimal lateral advection of all species by horizontal currents. As a consequence, no size- or shape-dependent sorting should occur in foraminiferal assemblages during deposition, making foraminifera ideal proxy carriers after correcting for post-depositional biases.

Printer-friendly Version

Interactive Discussion

Different particle groups exhibit a range of transport distances, diatoms, radiolaria and faecal pellets travelling up to 500 km in high-velocity areas, whilst foraminifera, marine snow and diatom aggregates travel at most 150 km. This suggests that different proxies based on a range of particle types could represent different catchment areas and hence result in a bias in the reconstructed environmental parameter. With transport within diatoms, radiolaria and faecal pellets also covering a wide range of distances depending on location, sediment assemblages will contain differing proportions of local and imported particles, introducing a margin of error in proxy reconstructions. South of the Agulhas current, this could lead to temperature reconstructions up to 2 °C warmer in a modern ocean.

References

Al-Sabouni, N., Kucera, M., and Schmidt, D.: Vertical niche separation control of diversity and size disparity in planktonic foraminifera, Mar. Micropaleontol., 63, 75–90, 2007. 6769

Alldredge, A. and Gotschalk, C.: In situ settling behavior of marine snow, Limnol. Oceanogr., 33, 339–351, 1988. 6770, 6778

Alldredge, A. and Gotschalk, C.: Direct observations of the mass flocculation of diatom blooms: characteristics, settling velocities and formation of diatom aggregates, Deep Sea Res., 36, 159–171, 1989. 6770, 6778

Alldredge, A., Granata, T. C., Gotschalk, C., and Dickey, T.: The physical strength of marine snow and its implications for particle disaggregation in the ocean, Limnol. Oceanogr., 35, 1415–1428, 1990. 6767

Battarbee, R., Mackay, A., Jewson, D., Ryves, D., and Sturm, M.: Differential dissolution of Lake Baikal diatoms: correction factors and implications for palaeoclimatic reconstruction, Glob. Planet. Change, 46, 75–86, 2005. 6765

Bé, A., Harrison, S., and Lott, L.: *Orbulina universa* d'Orbigny in the Indian Ocean, Micropaleontology, 19, 151–192, 1973. 6768

Benthien, A. and Müller, P.: Anomalously low alkenone temperatures caused by lateral particle and sediment transport in the Malvinas Current region, western Argentine Basin, Deep-Sea Res. Pt. I, 47, 2369–2393, 2000. 6771

Berger, W.: Planktonic foraminifera: selective solution and the lysocline, Mar. Geol., 8, 111–138, 1970. 6765

Berger, W. and Piper, D.: Planktonic Foraminifera: differential settling, dissolution, and redeposition, Limnol. Oceanogr., 17, 275–287, 1972. 6765

Berthois, L. and Le Calvez, Y.: Etude de la vitesse de chute des coquilles de foraminifères planctoniques dans un fluide comparativement à celle des grains de quartz, Revue des Travaux de l'Institut des Pêches Maritimes, 24, 293–301, 1960. 6765

Caromel, A. G. M., Schmidt, D. N., Phillips, J. C., and Rayfield, E. J.: Hydrodynamic constraints on the evolution and ecology of planktic foraminifera, in preparation, 2013. 6765, 6766, 6768, 6777

Chen, M.-T. and Prell, W.: Faunal distribution patterns of planktonic foraminifers in surface sediments of the low-latitude Pacific, Palaeogeogr. Palaeocl., 137, 55–77, 1998. 6765

Fok-Pun, L. and Komar, P.: Settling velocities of planktonic foraminifera: density variations and shape effects, J. Foramin. Res., 13, 60–68, 1983. 6765

Franzese, A., Hemming, S., Goldstein, S., and Anderson, R.: Reduced Agulhas Leakage during the Last Glacial Maximum inferred from an integrated provenance and flux study, Earth Planet. Sci. Lett., 250, 72–88, 2006. 6771, 6772

Hemleben, C., Spindler, M., and Anderson, O.: Modern Planktonic Foraminifera, Springer, New York, Berlin, Heidelberg, 1989. 6769

Henderson, G.: New oceanic proxies for paleoclimate, Earth Planet. Sci. Lett., 203, 1–13, 2002. 6764, 6765

Honjo, S.: Coccoliths: production, transportation and sedimentation, Mar. Micropaleontol., 1, 65–79, 1976. 6766

Kiorboe, T.: Small-scale turbulence, marine snow formation, and planktivorous feeding, Sci. Mar., 61, 141–158, 1997. 6767

Kiorboe, T., Lundsgaard, C., Olesen, M., and Hansen, J.: Aggregation and sedimentation processes during a spring phytoplankton bloom: a field experiment to test coagulation theory, J. Mar. Res., 52, 297–323, 1994. 6770

Komar, P. D. and Reimers, C. E.: Grain shape effects on settling rates, J. Geol., 86, 193–209, 1978. 6765

Kontrovitz, M., Snyder, S. W., and Brown, R. J.: Flume study of movement of foraminiferal tests, Palaeogeogr. Palaeocl., 23, 141–150, 1978. 6765

Kucera, M., Weinelt, M., Kiefer, T., Pflaumann, U., Hayes, A., Weinelt, M., Chen, M.-T., Mix, A., Barrows, T., Cortijo, E., Duprat, J., Juggins, S., and Waelbroeck, C.: Reconstruction of sea-surface temperatures from assemblages of planktonic foraminifera: multi-technique approach based on geographically constrained calibration data sets and its application to glacial Atlantic and Pacific oceans, Quat. Sci. Rev., 24, 951–998, 2005. 6765, 6766

Lande, R. and Wood, A.: Suspension times of particles in the upper ocean, Deep Sea Res., 34, 61–72, 1987. 6768

Little, M., Schneider, R., Kroon, D., Price, B., Bickert, T., and Wefer, G.: Rapid palaeoceanographic changes in the Benguela Upwelling System for the last 160,000 years as indicated by abundances of planktonic foraminifera, Palaeogeogr. Palaeocl., 130, 135–161, 1997. 6772

Locarnini, R., Mishonov, A., Antonov, J., Boyer, T., Garcia, H., Baranova, O., Zweng, M., and Johnson, D.: World Ocean Atlas 2009, Volume 1: Temperature, NOAA Atlas NESDIS 68, U.S. Government Printing Office, Washington, D.C., 2010. 6772

Lynch-Stieglitz, J., Curry, W., and Slowey, N.: Weaker Gulf Stream in the Florida Straits during the Last Glacial Maximum, Nature, 402, 644–648, 1999. 6772

MacIntyre, S., Alldredge, A., and Gotschalk, C.: Accumulation of marine snow at density discontinuities in the water column, Limnol. Oceanogr., 40, 449–468, 1995. 6768

McCave, I.: Size spectra and aggregation of suspended particles in the deep ocean, Deep Sea Res., 31, 329–352, 1984. 6770

McCave, I., Manighetti, B., and Robinson, S.: Sortable silt and fine sediment size/composition slicing: parameters for palaeocurrent speed and palaeoceanography, Paleoceanography, 10, 593–610, 1995. 6767

McNown, J. and Malaika, J.: Effects of particle shape on settling velocity at low Reynolds numbers, Transactions, American Geophysical Union, 31, 74–82, 1950. 6765

Ohkouchi, N., Eglinton, T., Keigwin, L., and Hayes, J.: Spatial and temporal offsets between proxy records in a sediment drift, Science, 298, 1224–1227, 2002. 6771

Peeters, F., Acheson, R., Brummer, G., de Ruijter, W., Schneider, R., Ganssen, G., Ufkes, E., and Kroon, D.: Vigorous exchange between the Indian and Atlantic oceans at the end of the past five glacial periods, Nature, 430, 661–665, 2004. 6769, 6772

Peters, F. and Redondo, J.: Turbulence generation and measurement: application to studies on plankton, Sci. Mar., 61, 205–228, 1997. 6767

Ross, O.: Particles in motion: How turbulence affects plankton sedimentation from an oceanic mixed layer, Geophys. Res. Lett., 33, L10609, 2006. 6767

Schmidt, D., Renaud, S., Bollmann, J., Schiebel, R., and Thierstein, H.: Size distribution of Holocene planktic foraminifer assemblages: biogeography, ecology and adaptation, Mar. Micropaleontol., 50, 319–338, 2004. 6768

Shemesh, A., Burckle, L., and Froelich, P.: Dissolution and preservation of Antarctic diatoms and the effect of sediment thanatocoenoses, Quat. Res., 31, 288–308, 1989. 6765

Smayda, T.: The suspension and sinking of phytoplankton in the sea, Oceanogr. Mar. Biol., 8, 353–414, 1970. 6778

Takahashi, K. and Honjo, S.: Radiolarian skeletons: size, weight, sinking speed, and residence time in tropical pelagic oceans, Deep Sea Res., 30, 543–568, 1983. 6770, 6778

Thiede, J.: Reworking in Upper Mesozoic and Cenozoic central Pacific deep-sea sediments, Nature, 289, 667–670, 1981. 6765

Ujiié, Y., Ujiié, H., Taira, A., Nakamura, T., and Oguri, K.: Spatial and temporal variability of surface water in the Kuroshio source region, Pacific Ocean, over the past 21,000 years: evidence from planktonic foraminifera, Mar. Micropaleontol., 49, 335–364, 2003. 6772

Weaver, A., Eby, M., Wiebe, E., Bitz, C., Duffy, P., Ewen, T., Fanning, A., Holland, M., MacFayden, A., Matthews, H., Meissner, K., Saenko, O., Schmittner, A., Wang, H., and Yoshimori, M.: The UVic Earth System Climate Model: model description, climatology, and applications to past, present and future climates, Atmosphere-Ocean, 39, 361–428, 2001. 6767, 6779

Yick, K. Y., Torres, C. R., Peacock, T., and Stocker, R.: Enhanced drag of a sphere settling in a stratified fluid at small Reynolds numbers, J. Fluid Mech., 632, 49–68, 2009. 6768

Yoon, W., Kim, S., and Han, K.: Morphology and sinking velocities of fecal pellets of copepod, molluscan, euphausiid, and salp taxa in the northeastern tropical Atlantic, Mar. Biol., 139, 923–928, 2001. 6770, 6778

Table 1. Settling velocity and size of nine species of planktic foraminifera (data from Caromel et al. (in preparation))

Species	Velocity m s^{-1}		Size (µm)		Velocity m day^{-1}	
	mean	min.-max.	mean	min.-max.	mean	min.-max.
Globigerinoides ruber	0.024	0.018–0.033	550.1	319.3–742.9	2073.6	1555.2–2851.2
Globigerinoides trilobus	0.026	0.019–0.039	437.5	259.2–680.3	2246.4	1641.6–3369.6
Globigerinoides sacculifer	0.030	0.022–0.038	688.4	411.7–953.7	2592.0	1900.8–3283.2
Orbulina universa	0.030	0.012–0.050	636.1	430.2-817.9	2592.0	1036.8–4320.0
Globorotalia menardii	0.032	0.017–0.041	1088.2	712.6–1589.3	2764.8	1468.8–3542.4
Globorotalia hirsuta	0.032	0.015–0.039	628.1	369.4–999.1	2764.8	1296.0–3369.6
Globorotalia truncatulinoides	0.040	0.025–0.050	626.1	467.8–760.2	3456.0	2160.0–4320.0
Globorotalia tumida	0.051	0.038–0.058	946.0	740.5–1334.2	4406.4	3283.2–5011.2
Globigerinoides conglobatus	0.053	0.035–0.068	597.7	468.6–794.6	4579.2	3024.0–5875.2

Table 2. Settling velocity of sedimenting particles of organic origin

Particle	Velocity m day^{-1}	Reference	Velocity m s^{-1}
Diatoms (dead)	6–60	(Smayda, 1970)	0.00007–0.0007
Diatoms (giant, dead)	<400		<0.0046
Diatom aggregates	117	(Alldredge and Gotschalk, 1989)	0.0014
Marine snow	74	(Alldredge and Gotschalk, 1988)	0.0009
Copepod fecal pellets	26.5–159.5 (avg 69.9)	(Yoon et al., 2001)	0.0003–0.0018 (avg 0.0008)
Euphausiid fecal pellets	16.1–341.1 (avg 122.3)		0.0002–0.0039 (avg 0.0014)
Nassellarian radiolaria	14–105		0.0002–0.0012
Spumellarian radiolaria	25–177	(Takahashi and Honjo, 1983)	0.0003–0.0020
Phaeodarian radiolaria	13–416		0.0002–0.0048
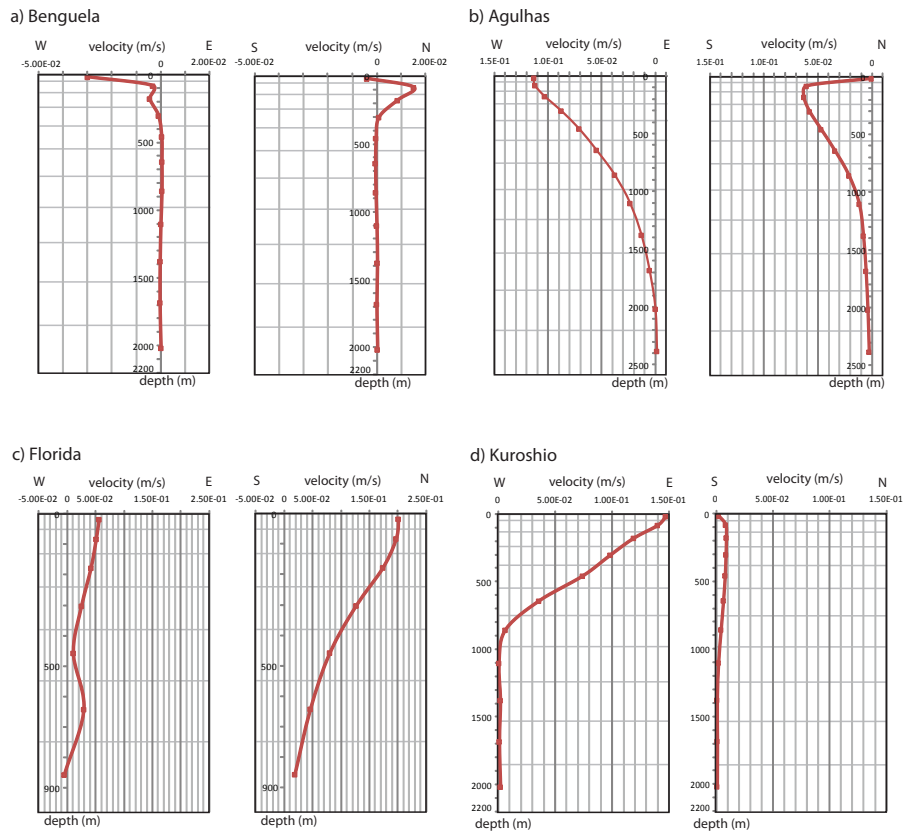
Fig. 1. Annual mean horizontal velocity depth profiles for the selected sites, extracted from a historical run (for the year 2000) of the UVic Earth System Climate Model version 2.9 (Weaver et al., 2001). The horizontal grey lines mark the depth intervals.
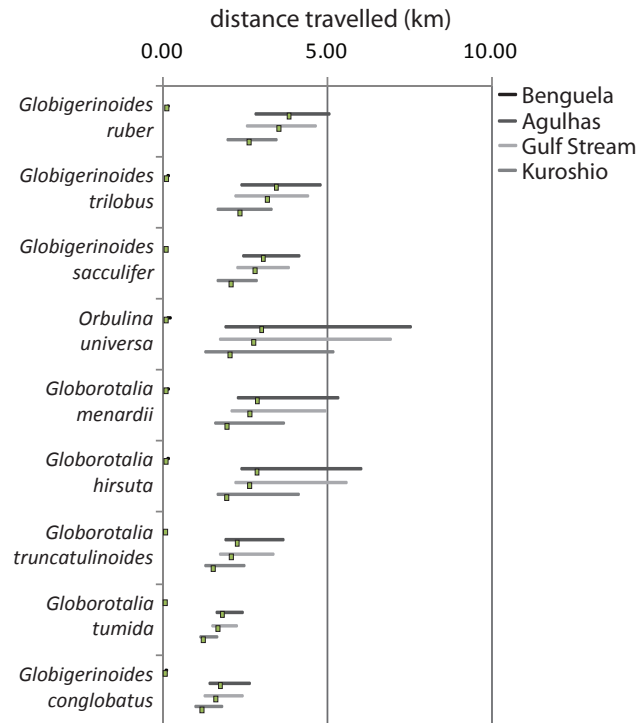
Fig. 2. Range of distances travelled by nine species of planktic foraminifera at the selected sites (green square represents the mean).
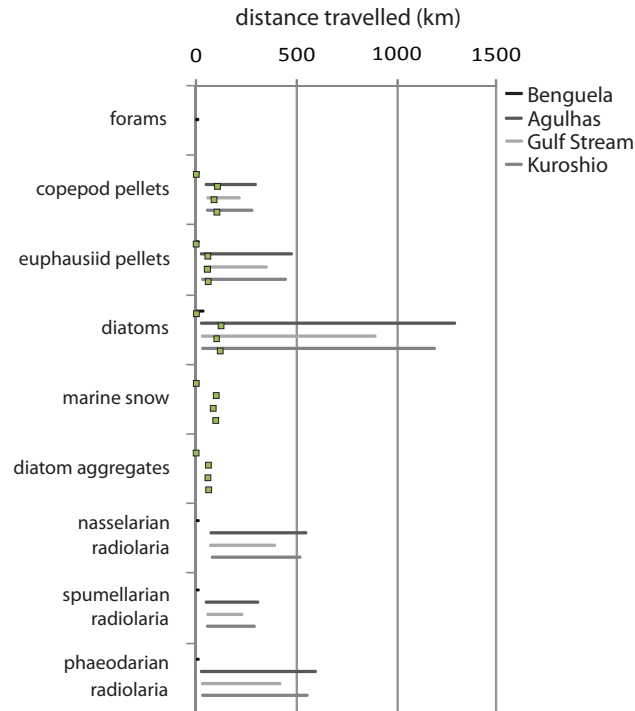
Fig. 3. Range of distances travelled by sedimenting particles of organic origin at the selected sites (green square represents a mean or single value in the case of marine snow and diatom aggregates).