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VARIATION OF SUSPENDED AND SEDIMENTARY ORGANIC MATTER WITH DEPTH IN SHALLOW COASTAL WATERS

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Abstract: I tested the hypothesis that the quantity and quality of suspended and sediment organic matter in shallow coastal waters is affected by wind-induced resuspension at a smaller depth scale (< 1 m) than usually assumed. Water and sediment surface (0 to 1 cm) samples were collected on a seasonal basis and analyzed for total suspended matter, organic fraction, and phytopigments at 12 shallow sites representing a depth gradient from 0.2 to 2.0 m along the western shore of Sicily. Water column concentrations of all measured variables decreased rapidly with increasing water column depth, and concentrations levelled off at about 1 m water column depth. The likelihood of sediment resuspension by wind for various combinations of water column depth and fetch length was modelled using the CERC (U.S. Army Corps of Engineers, Coastal Engineering Centre, Washington D.C. US) model for 10 years of local wind data. The simulations indicated that even light winds (2 m s^{-1}) increased the likelihood of resuspension in the shallowest basin (0.2 m depth) with an effective fetch of 250 m. This study provides evidence that shallow water systems should not be investigated by considering the entire water column as a single homogenous layer. Investigations of shallow water ecosystems should consider 2 main layers with different ecological conditions and functions: a shallow surface turbulent layer from the surface to a depth of 1 m that is strongly affected by wind-driven physical forces and a deeper, below 1 m to the sediment surface, layer where wind-driven turbulence has less impact.

Key Words: fetch, limnology, resuspension, Mediterranean, wave action

INTRODUCTION

Shallow waters house highly productive ecosystems, sustaining over the 90% of worldwide biodiversity in marine and aquatic ecosystems (Raffaelli et al. 2003). In most of these environments (lagoons, bays, estuaries and so forth; Booth et al. 2000, Poizat et al. 2004, Pusceddu et al. 2007), nutrient inputs of continental origin are the mainstays of local productivity and productivity is often salinity dependent (Day et al. 1989, Håkanson et al. 2007). However, there are several shallow water coastal ecosystems that do not receive nutrients from fresh water inflow and lack sharp salinity gradients (Håkanson et al. 2007). Despite their productivity, they are often overlooked as unique coastal ecosystems. High levels of productivity of 'freshwater-free' shallow ecosystems can be induced 1) by organic waste input from aquaculture activities (Sarà 2007a), 2) exchange of organic matter with nearby highly productive areas (Ray and Straskraba 2004), or 3) highly enriched harbors or bays (e.g., Halldórsson et al. 2008). Under such limnological conditions, the only possible nutrient sources are from adjacent systems or *in situ* organic matter decomposition in sediments (Pusceddu et al. 2003). Generally, marine autochthonous or human derived organic matter generally remains entrapped in bottom sediments unless biological activity (burrowing or bioturbation) and/or physical factors like wind-driven resuspension facilitate its extraction (Sarà 2006).

In shallow, small, or atidal coastal environments, hydrodynamic regimes can be turbulent. Wind-driven sediment resuspension is among the dominant physical processes (Ward 1980) and is a key factor affecting local productivity (Judge et al. 1992, Robbins and Bell 2000, Yahel et al. 2000, Shimeta et al. 2002). Wind works like an environmental washing machine, re-arranging sediments by resuspension, modifying their features along a spatio-temporal continuum, and affecting the properties of the water column. The extent of wind effects on sediment turnover and organic matter extraction from the sediment is a function of water column depth (Smaal and Haas 1997, Booth et al. 2000). To date, the "depth" gradient has rarely been considered as the physical cause of variation in the productivity and distribution of species (e.g., Webb and D'Elia 1980, Court Stevenson 1988, Day et al. 1989, Robbins and Bell 2000, Sochu et al. 2001), although it is an important formal parameter in most numerical models (e.g., Hawley and Lesht 1992, Pringle and Franks 2001, Beaulieu 2003, Håkanson 2006). The literature does not specifically allude to the depth gradient effect on productivity (Butman et al. 1994, Håkanson 2006), but typically considers shallow waters as a single horizontal layer from a few cm to 4 meters depth. Thus, the term "shallow zones" is rather general, as most of them are found in the first shallow layer of the surface of the water (i.e., a few cm to 1 m). However, in depths between 1 to 2 and 4 m, ecological processes assume a different nature. The limnology of the layers of water is pelagic-oriented rather than benthic-based and functional and behavioral aspects of organisms change definitively. Resuspension, controlling the ecological aspects of most shallow biodiversity, is a wind-depth dependent process and its magnitude decreases as a function of depth.

I hypothesize that the quantity and quality of suspended and sediment organic matter varies as a function of water column depth, and while significant changes occur in the shallowest areas, the effects due to wind-induced sediment resuspension tend to be less evident in deeper areas. The data supports the ideas that in certain temperate shallow coastal ecosystem waters, where the terrestrial inputs are absent or negligible, 1) organic matter availability varies with depth, 2) the total suspended matter, organic fraction, and phytopigments provide reliable records of potential differences within the first meter below the water surface of the water column, and 3) the likelihood of sediment resuspension by wind, modelled using the CERC (U.S. Army Corps of Engineers, Coastal Engineering Centre, Washington D.C., U.S.) model for 10 years of local wind data, varies as a function of various combinations of water column depth and fetch length.

METHODS

Study Area

The study was conducted in the most important pond system for avifauna stopover habitat in the western Mediterranean (Mannino and Sarà 2006). The area consists of about 25 constructed ponds, covering a surface area of ca. 1500 ha, and the largest lagoon in western Sicily, the Stagnone di Marsala (western Sicily, 37° 52′ North; 12° 28′ East) (Pusceddu et al. 2003, Sarà 2006). The pond system was created in the 15th century for salt production and the topography, basin structure, and hydraulic system of water distribution have remained more or less unchanged since that time (Mannino and Sarà 2006). The study ponds obtain water directly from the sea through channels, with salinity similar to or slightly higher than seawater (Mannino and Sarà 2006). Basins are essentially atidal with internal currents mostly driven by winds (Sarà 2006). All study ponds have sandy-muddy bottoms extensively colonized by meadows of *Ruppia maritima* and *Cymodocea nodosa* with abundant macroalgal mats (Mannino and Sarà 2006). Other topographical, chemical, and physical characteristics of the Stagnone di Marsala are available in Pusceddu et al. (2003), La Loggia et al. (2004), and Sarà (2006).

Experimental Hypotheses and Design

I hypothesize that organic matter changes as a function of water depth within a range from 0.2 to 2 m. To tests this, I chose sites over a gradient composed of 6 depths (2 of each): 0.2, 0.4, 0.6, 0.8, 1.0, and 2.0 m. Prior to this study, depth measurements had been collected manually during 3 periods (August and December 2004, March 2005) at a minimum of 40 points in each pond. Data used to classify experimental depths in this study are the mean of these measures (± 3 cm). Due to the structure and morphology of the pond system, depth did not vary seasonally, apart from slight variations in summer, when evaporation can modestly lower the water level. By opening small locks during these periods, the original water levels of ponds can be restored. Tidal amplitude had some effect, particularly on the 0.2 and 0.4 m experimental depths. Because of the constant re-equilibration of the water level and the very small tidal amplitude at these Mediterranean latitudes (La Loggia et al. 2004), it was not a major influence.

For each depth level up to 1 m depth, I chose 2 ponds (n = 10). The 2 m depth sites were located in the adjacent lagoon. Similar conditions of fetch and vegetation existed in both the constructed ponds and the natural coastal lagoon.

Sampling and Laboratory Analyses

At each site, 2 replicates of water and sediments were collected seasonally from spring 2005 to winter 2006. All samples were always from areas with similar vegetation biomass and cover (Mannino and Sarà 2006). Water samples were collected by hand using a Niskin bottle. PVC tubes (i.d. 4.7 cm) were manually inserted into the bottom to collect sediment cores. Sub-samples of water (500 to

2000 ml) were filtered onto pre-washed, precombusted (450°C, 4 h) and pre-weighed Whatman GF/F filters (0.45 μm nominal pore size). The top 0 to 1 cm layer of each core was immediately frozen at −20°C and stored for later analysis. Water samples were analyzed to determine total suspended matter (TSM) and its organic fraction (OSM), as well as chlorophyll-a (CHL-a) and phaeopigment (PHAEO) concentrations. Sediments were analyzed for total organic matter and CHLa and PHAEO contents. TSM was determined gravimetrically by desiccation (105°C, 24 h) using a Mettler balance (accuracy ± 1 μg). The organic fraction of seston (OSM; mg l^{-1}) was determined by loss on ignition (450°C, 4 h) and the material remaining after combustion is reported as the inorganic suspended fraction (ISM; mg l^{-1}). Sediment samples were screened through a 500 μm mesh net to remove large debris, algae fragments, and seagrass leaves and roots, and the total organic fraction thereof (SOM, mg g^{-1}) was determined gravimetrically following the same method as for TSM. Suspended CHL-a was determined according to Lorenzen and Jeffrey (1980), while sedimentary CHL-a and PHAEO were determined according to Pusceddu et al. (2003) and Sarà (2006). All analyses were carried out in triplicate.

Modelling of Wind Resuspension

The relative likelihood of sediment resuspension by wind was modelled with the CERC model (1984). Data on wind were obtained from a decadal meteorological series available from the Birgi Airport Meteorological Public Station, which is a few km from the study area. Wind was also expressed as fetch length. Wind data were combined with water column depth according to the CERC approach (1984). The CERC model has been evaluated in coastal and lacustrine environments, and the results to estimate when the base of a wave extends to the bottom of the water column, and re-suspension is expected have been shown to fit well with field measurements (Carper and Bachmann 1984, Shideler 1984, Demers and Therriault 1987, Simon 1989, Arfi et al. 1993, Booth et al. 2000). As the wave base is supposed to be 0.5 wave length, resuspension will happen when wave length (L) exceeds the water column depth (h) by a factor of 2 ($L/h > 2$). L (m) depends on the wave period, which is calculated from wind velocity and fetch by an empirical relation (CERC 1984): $gT/2\pi U = 1.2$ tangent h $(0.077\ (gF/U^2)^{0.25})$, where g is gravitational constant (9.8 m s^{-2}), T is wave period (s), U is wind velocity (m s^{-1}), and F is fetch (m). Wave length is calculated as: $L = gT^2/2\pi$.

Statistical Analysis

Data were analyzed in order to test the null hypothesis that there is no difference in suspended and sedimentary concentrations of all investigated variables among depths and seasons, using a 2-way ANOVA. Thus, Depth (6 levels) and Season (4 levels) were treated as fixed factors. Three replicates were used for each variable. For all of the analyses, the heterogeneity of variances was tested using Cochran's C test prior to the ANOVA, and the Student-Newman-Keuls (SNK) test was used to separate means. GMAV rel 5.0 (University of Sydney) was used to perform ANOVAs. The same design was used in the case of permutational multivariate analysis of variance (PERMANOVA, Anderson 2001). Variables were ln (y + 1) transformed to retain information on relative concentrations but reduce differences in scale among the variables. The Euclidean similarity measure was used, and all p-values were calculated using 9999 permutations of the residuals under a reduced model (Anderson 2001). Differences between depths and seasons were examined in more detail using a canonical analysis of principal coordinates (CAP) and pair-wise tests (Anderson and Willis 2003).

RESULTS

Organic Matter as a Function of Depth

All the variables measured to test the effect of depth on suspended matter showed a similar pattern: the shallower the depth and closer to the surface, the higher the concentrations (Table 1; see regressions in Figure 1a–f). Apart from a few exceptions, the result was the same: concentrations were not significantly different among basins from 0.2 m to 0.8 m, while a sharp and significant decline in concentrations was seen at depths of 2 m in deeper basins (see SNK test inside Figure 1). All variables showed high variability (high errors for means; e.g., Figure 1a) in shallower basins, while the variability around means decreased in the deepest ones. This was especially evident for water column variables whereas sediment variability was of lower magnitude. Only chlorophyll-a in the water column and the sediment showed significant seasonal changes (ANOVA, $p < 0.05$). Suspended inorganic fraction (ISM) showed a non-significant increase from shallower to greater depths (Table 2), coupled with a decrease in organic matter. The chlorophyll-a

Table 1. Statistics of all variables measured in the study area as a function of varying depth (TSM = total suspended matter; ISM = inorganic fraction of total suspended matter; OSM = organic fraction of total suspended matter; %ISM = inorganic percentage of TSM; %OSM = organic percentage of TSM; SUSP CHL-a = suspended chlorophyll-a; SED CHL-a = sedimentary chlorophyll-a; PHAEO = sedimentary phaeopigments; SOM = sedimentary organic matter).

	TSM (mg l^{-1})		ISM (mg l^{-1})		OSM (mg l^{-1})	
Depth	mean	± se	mean	± se	mean	± se
0.2	148.1	74.1	36.5	11.8	111.6	35.9
0.4	78.3	33.3	34.2	13.2	44.1	25.8
0.6	79.8	21.9	35.4	15.4	44.4	14.8
0.8	60.8	25.3	36.7	19.2	24.0	9.1
1.0	3.0	0.2	1.8	0.2	1.3	0.2
2.0	2.5	0.3	1.6	0.3	1.0	0.2
	%ISM		%OSM		SUSP CHLA (μg l^{-1})	
0.2	41.4	17.1	58.6	17.1	33.8	14.3
0.4	54.4	19.6	45.6	19.6	15.5	6.7
0.6	47.3	21.8	52.7	21.8	14.2	6.4
0.8	59.7	21.3	40.3	21.3	9.8	7.3
1.0	58.1	18.3	41.9	18.3	0.4	0.1
2.0	60.2	19.8	39.8	19.8	0.3	0.1
	SED CHLA (μg l^{-1})		PHAEO (μg l^{-1})		SOM (mg g^{-1})	
0.2	17.6	2.3	45.8	6.7	43.8	1.9
0.4	13.2	1.7	30.9	3.9	41.4	3.1
0.6	14.0	2.3	33.1	5.4	40.5	6.6
0.8	7.5	2.2	18.3	6.7	24.5	6.7
1.0	5.6	2.4	4.1	1.0	7.1	0.9
2.0	6.6	1.7	3.4	0.7	46.4	8.9

to phaeopigment ratio was always less than 1 in shallower basins (< 0.8 m depth), while it was greater than 1 in deeper basins. Sedimentary organic matter showed a strong negative linear relationship with depth to 1 m (see Figure 1f), but after that, it decreased significantly reaching almost the same concentration observed at lower depths.

ANOVA, PERMANOVA, and CAP analyses confirmed that the general dynamics in water columns and sediments at lower depths were significantly different from those at greater water column depths. In particular, CAP (Figure 2) clustered sites with the shallowest depths together and demonstrated a seasonal pattern (Table 3). In general, spring and summer concentrations were higher than autumn and winter concentrations, but within each season, the overall depth-related pattern of all of the investigated variables did not change.

Simulated Relationships among Depth, Water Fetch, Wind, and Resuspension

The frequency of wind intensity, regardless of direction, extrapolated from a decadal series (1997–2006) shows that the wind was light (1 to 4 m s^{-1}) 70% of the time, with 2 m s^{-1} speeds occurring most frequently (Figure 3,). Wind blew moderately (5 to 7 m s^{-1}) 21% of the time, while over the remaining 9%, it reached intensities of 8 to 14 m s^{-1}. Wind intensity at 2 m s^{-1} is able, according to the CERC formula, to increase the likelihood of resuspension in basins of 0.2 m depth, with an effective fetch of 250 m. However, an intensity of 4 m s^{-1} is required to induce resuspension at 0.4 m basins, 5 m s^{-1} at 0.6 m, and 6 m s^{-1} at 0.8 m (Table 4). To induce resuspension at depths > 1 m, wind velocity had to reach 8 m s^{-1} (3.3% of cases; fetch 250 m; Table 4), and winds of > 15 m s^{-1} are required to induce sediment resuspension (a wind speed considered very infrequent for the study area (Figure 3). Thus, the greater the fetch, the higher the resuspension likelihood: while basins < 1 m reached resuspension within a wind speed range of 2 to 6 m s^{-1}, basins 2 m deep needed wind speeds over 11 m s^{-1} to resuspend sediments.

DISCUSSION

My study indicates that within the first 0.2 to 2 m below the surface adopting micro-scale depth

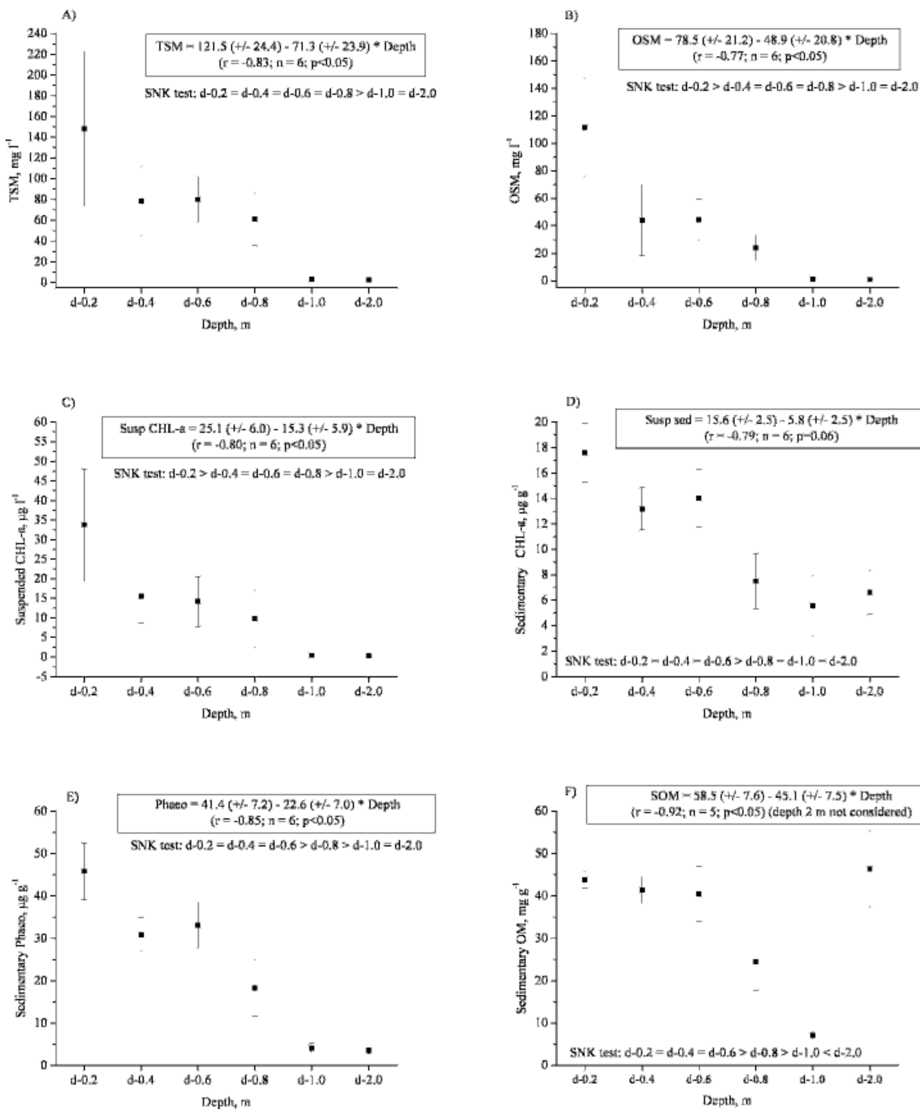

Figure 1. Relationships among water column and sedimentary variables and depth (d-x); A) suspended matter (TSM), B) suspended organic matter (OSM), C) suspended chlorophyll-a (susp-CHL-a), D) sedimentary chlorophyll-a, E) suspended phaeopigments, and F) suspended organic matter (OSM).

resolution is preferable to considering shallow waters as a single homogeneous layer. Shallow waters show profound differences in their dynamics along a depth gradient within the first 2 m (*sensu* Butman et al. 1994). The relationship between depth, wind, waves, and resuspension from sediments have been investigated in several studies (e.g., Hellström 1991, Kristensen et al. 1992, Håkanson 2006, Håkanson et al. 2007). From these, it can be derived that a high wind speed increases suspended matter concentrations. Wind direction can also be important: if the fetch is wide, the wave base (i.e., the water column depth to which the wave orbital can resuspend fine particles) can be deep, and if the wave base is deeper, the likelihood of resuspension of sediments increases. Thus, the characteristics of the water within the first meter below the surface of shallow waters are profoundly different from deeper water due to the effect of shear stress induced by wind, which affects resuspension of sedimented organic matter from the bottom. This supports the conclusion that wind-wave-forced sediment resuspension is a main enrichment factor of the water column in shallow waters (Sanford 1994, Leonard and Luther 1995, Shimeta et al. 2002, Sarà 2006), and also shows that the greater the increase in mean flow turbulent speed, the greater the increase in the water-column turbidity (Booth et al. 2000, Beaulieu 2003).

The first meter of water throughout the study area had high concentrations of suspended sedimentary material. Indirectly, this would imply high levels of

Table 2. ANOVA carried out on environmental variables in the study area to test whether depth had an effect in determining the trophic availability (TSM = total suspended matter; ISM = inorganic fraction of total suspended matter; OSM = organic fraction of total suspended matter; S-CHL-a = suspended chlorophyll-a; Sed CHL-a = sedimentary chlorophyll-a; PHAEO = sedimentary phaeopigments; SOM = sedimentary organic matter; ns = no significant difference; * = difference at $p < 0.05$; ** = difference at $p < 0.01$; *** = difference at $p < 0.001$; ξ = data transformed to log[x + 1]).

		TSM			ISM			OSM			S-CHL-a		
Source	df	MS	F	P	MS	F	P	MS	F	P	MS	F	P
Season	3	0.5	0.4	ns	753.1	0.5	ns	1.7	1.5	ns	10.5	11.2	***
Depth	5	18.8	15.9	***	2480.3	1.8	ns	14.4	12.1	***	16.2	17.4	***
Season × Depth	15	0.8	0.7	ns	1018.8	0.7	ns	0.9	0.8	ns	1.9	2.0	ns
Residuals	24	1.2			1403.6			1.2			0.9		
Cochran's C				ns (ζ)			ns			ns (ζ)			ns (ζ)

		Sed-CHL-a			Sed PHAEO			SOM		
Source	df	MS	F	P	MS	F	P	MS	F	P
Season	3	0.9	3.4	***	0.9	1.4	ns	140.6	0.6	ns
Depth	5	2.3	8.6	***	8.8	14.3	***	1854.2	8.1	***
Season × Depth	15	0.4	1.7	ns	0.2	0.3	ns	284.2	1.2	ns
Residuals	24	0.3			0.6			228.3		
Cochran's C				ns (ζ)			ns (ζ)			ns

turbidity in the first meter (Håkanson 2006), which would decline in the water column depth below this level (Booth et al. 2000). However, bed flow speed under wind conditions throughout the study area should be within the appropriate critical range (0.1 to 10 cm s^{-1}) to elicit surface mixing (Webster and Hutchinson 1994) and resuspension of sedimentary particles (e.g., Andersson 2000, Booth et al. 2000, Beaulieu 2003, Shimeta et al. 2002, La Loggia et al. 2004, Sarà 2006). In the study area, wind conditions and fetch that could increase the likelihood of resuspension were the most frequent within 1 m of the surface (see Figure 3, Table 4). In contrast, conditions for resuspending material from the bottom below 1 m were infrequent. This relationship between wind velocity and resuspension of sediment at such a fine scale has not been previously reported and most authors considered the shallow zone as homogeneously undifferentiated from 0.2 m downwards (Lee et al. 1987, Leonard and Luther 1995, Lindell et al. 1996, Madden et al. 1998).

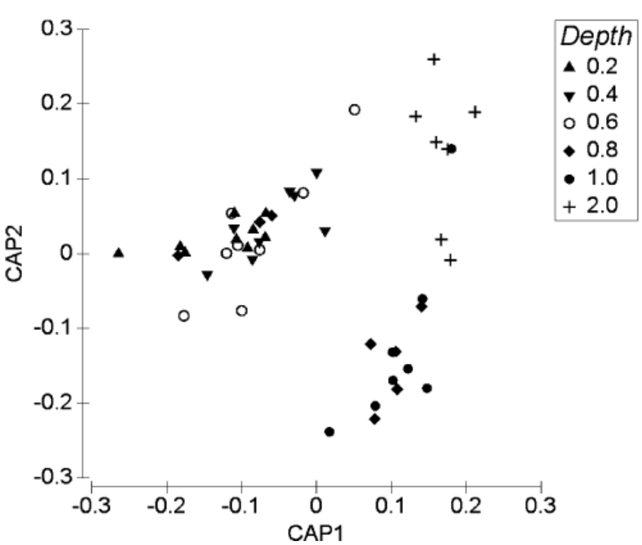

Figure 2. Canonical analysis of principal coordinates (CAP) (depth reported as m).

My analyses demonstrate significant effects on the features of suspended matter at different depths. At depths less than 1 m, suspended matter appears to be continually influenced by turbulence and suspended matter concentrations were very high. All water column variables measured in this study demonstrated the same pattern, and statistical outcomes support the argument that concentrations from the surface to < 1 m in depth were overall significantly different from depths greater than 1 m. Depth is often the most important predictor of the extent of bottom-up processes in shallow areas regarding, for example, primary production (Sochu et al. 2001) and bacterial activity (Bouvy et al. 1998).

Table 3. PERMANOVA outcome carried out on log-transformed the trophic matrix considering ISM, OSM, suspended CHL-a, sedimentary CHL-a, sedimentary phaeopigments and sedimentary organic matter (SOM). The analysis was performed with 9999 permutations and the Euclidean distance was used.

Source	df	MS	Pseudo-F	P(perm)
Season	3	11.1	2.8	0.006
Depth	5	47.4	12.0	0.000
Season × Depth	15	3.5	0.9	0.662
Residuals	24	4.0		

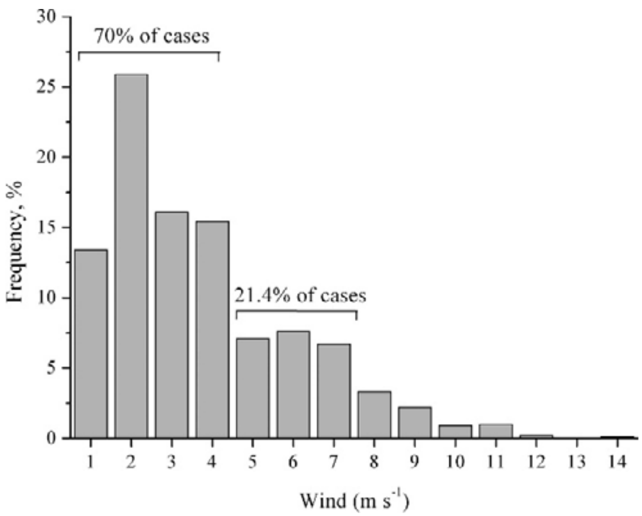

Figure 3. The frequency of wind intensity regardless of direction extrapolated from a decadal series (1997–2006).

Throughout my study area, TSM, its organic fraction and phytopigments showed important patterns of variability according to depth. In addition, the inorganic fraction of TSM (ISM) showed that within the top 0.8 m, the physical extraction from sediments was constant and declined below 1 m. Dynamics within 1 m were highly variable (Figure 1). Within 1 m of depth, sediments were the most important provider of organic matter to the water column. It can be assumed that, deeper than 0.8 m, the magnitude of the wind-depth-resuspension combined factor decreased and turbulence was not able to continue the extraction of matter from sediments.

It is likely that other physical phenomena (e.g., lateral advection; Sarà 2006) would assume increasing importance below 1 m. Stable isotopic evidence (Sarà 2006, 2007b) support this, as within 1 m of depth, the origin of organic matter available for mussels and cockles was of sedimentary origin (i.e., sand microflora). Other findings coming from many other very shallow areas worldwide confirm this: the shallower the depth, the larger the contribution of benthic organic material to secondary consumers (Herman et al. 2000, Sauriau and Kang 2000). All variables in the current study showed that the shallower the depth, the higher the concentrations, and this relationship was significant (Figure 1). Thus, phytopigments and total organic matter of sediments concentrations declined below 1 m. At 1 m and below, the bottom contribution slowly diminished to very low levels at 2 m depth.

With increasing depth, the pelagic contribution was more evident, slowly adding to the sedimentary contribution. In particular, SOM showed that the decline was constant up to 1 m, and at 2 m the physical effect exerted by wind ceased, resulting in organic matter accumulation which is consistent with the results of Pusceddu et al. 2003. Consequently, SOM at 2 m remained trapped in the sediments (see the peak of concentration for SOM;

Table 4. Wind intensity increases likelihood of resuspension as modelled by CERC formula (i.e., L/h > 2) at experimental depths with 250 and 500 m of fetch (the most probable fetch observed in the study area). Marked in grey are the first value of L/h which is > 2, meaning that likelihood of resuspension is high. (U, m s^{-1} = wind velocity; % freq. = frequency of that wind class in the study area [Birgi Airport] at 10 m above the sea surface extrapolated from a decadal series [1997–2006]).

Fetch 250 m		Depth (m)						**Fetch 500 m** U[m s^{-1}]		Depth (m)					
U[m s^{-1}]	%freq	0.2	0.4	0.6	0.8	1.0	2.0		%freq	0.2	0.4	0.6	0.8	1.0	2.0
1	13.4	1.1	0.6	0.4	0.3	0.2	0.1	1	13.4	1.5	0.7	0.5	0.4	0.3	0.1
2	25.9	2.5	1.2	0.8	0.6	0.5	0.2	2	25.9	3.4	1.7	1.1	0.8	0.7	0.3
3	16.1	3.8	1.9	1.3	1.0	0.8	0.4	3	16.1	5.3	2.6	1.8	1.3	1.1	0.5
4	15.4	5.2	2.6	1.7	1.3	1.0	0.5	4	15.4	7.2	3.6	2.4	1.8	1.4	0.7
5	7.1	6.5	3.3	2.2	1.6	1.3	0.7	5	7.1	9.1	4.5	3.0	2.3	1.8	0.9
6	7.6	7.9	3.9	2.6	2.0	1.6	0.8	6	7.6	11.0	5.5	3.7	2.7	2.2	1.1
7	6.7	9.2	4.6	3.1	2.3	1.8	0.9	7	6.7	12.9	6.4	4.3	3.2	2.6	1.3
8	3.3	10.6	5.3	3.5	2.6	2.1	1.1	8	3.3	14.8	7.4	4.9	3.7	3.0	1.5
9	2.2	11.9	6.0	4.0	3.0	2.4	1.2	9	2.2	16.7	8.4	5.6	4.2	3.3	1.7
10	0.9	13.3	6.6	4.4	3.3	2.7	1.3	10	0.9	18.6	9.3	6.2	4.7	3.7	1.9
11	1.0	14.6	7.3	4.9	3.7	2.9	1.5	11	1.0	20.5	10.3	6.8	5.1	4.1	2.1
12	0.2	16.0	8.0	5.3	4.0	3.2	1.6	12	0.2	22.5	11.2	7.5	5.6	4.5	2.2
13	0.0	17.3	8.7	5.8	4.3	3.5	1.7	13	0.0	24.4	12.2	8.1	6.1	4.9	2.4
14	0.1	18.7	9.3	6.2	4.7	3.7	1.9	14	0.1	26.3	13.1	8.8	6.6	5.3	2.6

Table 1; Figure 1f). The same effect was evident, but at a lower magnitude, for sedimentary chlorophyll-a, which showed a slight increase in its concentration at 2 m (6.6 μg g^{-1}; Figure 1d). This would suggest that, at 0.8 to 1.0 m, dynamics change, and contribution of sedimentary bulk to the water column declines. This permits the assumption that below 2 m, patterns stabilize (as demonstrated by smaller errors around means; Figure 1) due to the decreasing effect of the wind-depth-resuspension combined factor.

In conclusion, given that shallow waters are the worldwide dominion of turbidity (disregarding habitat complexity or habitat type), the shallow zone could be divided into 2 main layers dominated, in theory, by different ecological services and functions (*sensu* Håkanson et al. 2007; Craft et al. 2009). The first ''very shallow turbulent surface layer'', not more than 0.8 to 1.0 m depth from the surface and of variable width (depending on coastal morphology), would be the dominion of very shallow turbulent waters strongly affected by wind-driven physical forces (Sarà 2006, 2007b). Here, resuspension would be the major physical mechanism generating high levels of turbidity, which would dominate biological and ecological processes. This first layer would be characterized by high levels of undifferentiated organic matter of bentho-pelagic origin and it would serve as the real ''nursery and pantry'' (*sensu* Håkanson 2006). A second, deeper area (i.e., ''shallow stable layer'' from 0.8 to 1.0 m down to 4 m) could be identified, where the direct effect of turbulent physical extraction would slowly decline. In this case, the height of the water column is crucial, and waters would assume other characteristics. The importance of turbidity would slowly decrease and ecological functions and services would change. This is a habitat where bottom and water column would slowly uncouple as the bottom contribution declines.

The differentiation described herein should be considered in the building and applying of ecological models regarding shallow dynamics for worldwide ecosystems (Craft et al. 2009). Under these environmental conditions, we cannot consider shallow waters as a single homogenous layer at least from 0.2 to 2.0 m. On the other hand, the mean depth of shallow zones in many papers is about 1 m (also according to many diverse definitions) and this depth represents about 33–50% of total variability explained by the whole system. Since the ''very shallow turbulent layer'' often represents the widest part of many shallow zones (e.g., most of the salt marshes, tidal flats, lagoons, ponds, creeks, sand flats, and saltpans in the world), to disregard it could have profound implications on our knowledge of shallow water dynamics and for describing habitats, rates of production, and ecological functions. I recommend that in future studies the water column not be assumed to be homogeneous. These results emphasize that the first meter of the water column should be separated. Not doing so (i.e., reporting only the mean depth; see Sheaves 2001 for a review) could render a grossly inaccurate interpretation and be misleading.

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