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Entropy analysis of in situ particle size spectra

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Abstract

Entropy analysis has been used to classify in situ particle (floc) size spectra of suspended particles into groups based on similar distribution characteristics. Results revealed that the in situ spectra sorted into groups that reflected different forcing conditions (e.g. variations in turbulence). The different forcing conditions were not necessarily reflected in other commonly used distribution measures such as median floc diameter. This suggests that entropy analysis may be an effective approach for investigating the effect of changes in forcing conditions on floc size. It is hypothesized that it may be possible to derive the average shape of floc size spectra from measurement of the forcing conditions alone and subsequently derive parameters such as floc fraction, floc density, floc settling velocity and the optical properties of the water column from the average spectra.

Keywords: entropy; flocculation; statistics; in situ particle size; turbulence; suspended sediment

1. Introduction

The in situ particle size spectrum of suspended particulate matter in aquatic environment is of importance for sedimentological processes (Hill et al., in press), and it affects the transmission and reflectance of light in water (Mikkelsen, 2002; Flory et al., 2004). It also influences the feeding pattern of bottom fauna (Cranford et al., 2005). The in situ size spectrum of suspended matter in the aquatic environment differs from the size spectrum measured in the laboratory due to flocculation, which is the process that repackages small particles into large agglomerations bound with organic matter. The agglomerations are known as "flocs". Flocculation is active in freshwater, estuarine, and marine environments (Bale and Morris, 1987; Mikkelsen and Pejrup, 2001; Fox et al., 2004). The largest particles in the in situ size spectrum dominate the flux of particulate matter to the bottom (Van Leussen, 1994). The smallest particles in the spectrum, because they are numerically abundant and have large surface area, control the transmission and reflectance of light in the water column (Bale et al., 1994). Consequently the entire shape of the in situ size spectrum is of interest for the study of a wide range of processes.

Because flocs are disrupted during sampling (Bale and Morris, 1987), their size distribution must be measured in situ. To that end numerous types of instruments have been developed, notably instruments based on in situ photography (Milligan, 1996) or laser diffraction (Bale and Morris, 1987; Agrawal and Pottsmith, 2000). These instruments typically output the in situ particle area or volume distribution in a number of size bins.

Particle size spectra are often described simply by the mean or median particle size and perhaps a standard or median absolute deviation (Hill et al., 2000; Mikkelsen and Pejrup, 2000; Agrawal and Traykovski, 2001). However, as demonstrated by Sharp and Fan (1963) these parameters can be

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incomplete or even misleading descriptors of the shape of the size spectrum. For example, multi-modal in situ size spectra often exist (Mikkelsen and Pejrup, 2001; Mikkelsen et al., 2005), which obviously do not conform to the log-normal distribution for which mean and standard deviation are useful measures.

The need to represent the entire size distribution was addressed recently by Mikkelsen et al. (2006) by assigning volume to three classes: single grains, with diameters less than 36 μm, microflocs, with diameters between 36 and 133 μm, and macroflocs, with diameters greater than 133 μm. This division of volume was based on the conceptual model of Eisma (1986). Mikkelsen et al. (2006) obtained in situ particle size spectra by deploying the INSSECT tripod (IN situ Size and SEttling Column Tripod; Mikkelsen et al., 2004) at several sites on the shallow continental shelf of the western Adriatic Sea. The INSSECT was equipped with a LISST-100 (Agrawal and Pottsmith, 2000) and a digital floc camera (DFC, described in detail by Mikkelsen et al., 2004). A range of conditions were observed during four multi-day deployments. Conditions were calm for two deployments near the Pescara River and for another, near the Po River (Fig. 1). During a deployment near the Chienti River, a gale passed through the region, causing the only significant natural resuspension event during the various deployments (Fig. 2). Associated with the resuspension event was an increase in the relative and absolute volumes in the microfloc size class together with a decrease in the relative and absolute volumes of flocs >500 μm, which was interpreted to be a product of macrofloc break-up and erosion of microflocs from the seabed (Mikkelsen et al., 2006). Size spectra during resuspension differed from spectra that had the same median size before and after resuspension, thus demonstrating the advantage of extending characterization of the size distribution beyond simple single parameters (Fig. 2).

The division of volume into single grains, microflocs, and macroflocs is useful, but it can also provide incomplete or misleading descriptions of particle size. For example, consider

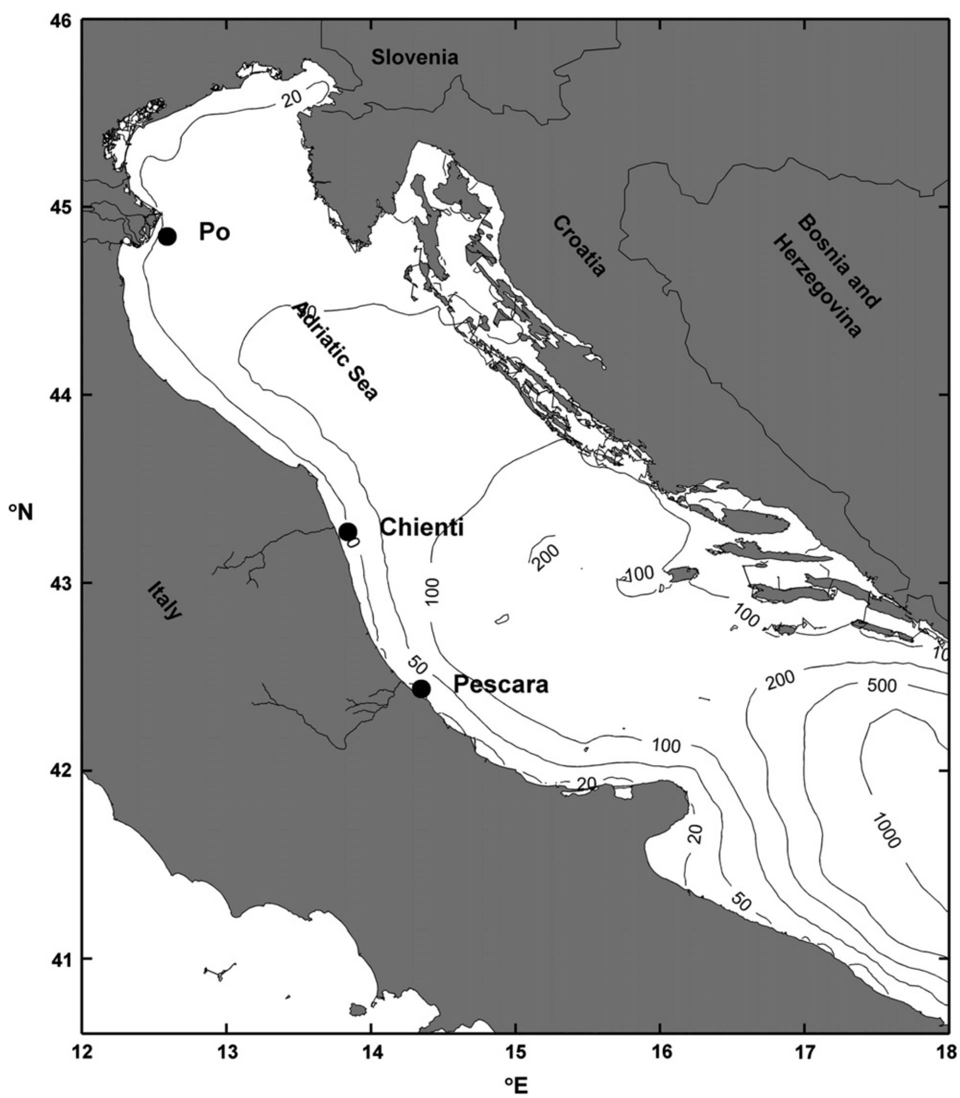

Fig. 1. Map of the study areas showing the region around the Po, Pescara and Chienti Rivers in the Adriatic Sea. Deployments took place off all three rivers, but only results from off the Chienti River are considered in this paper.

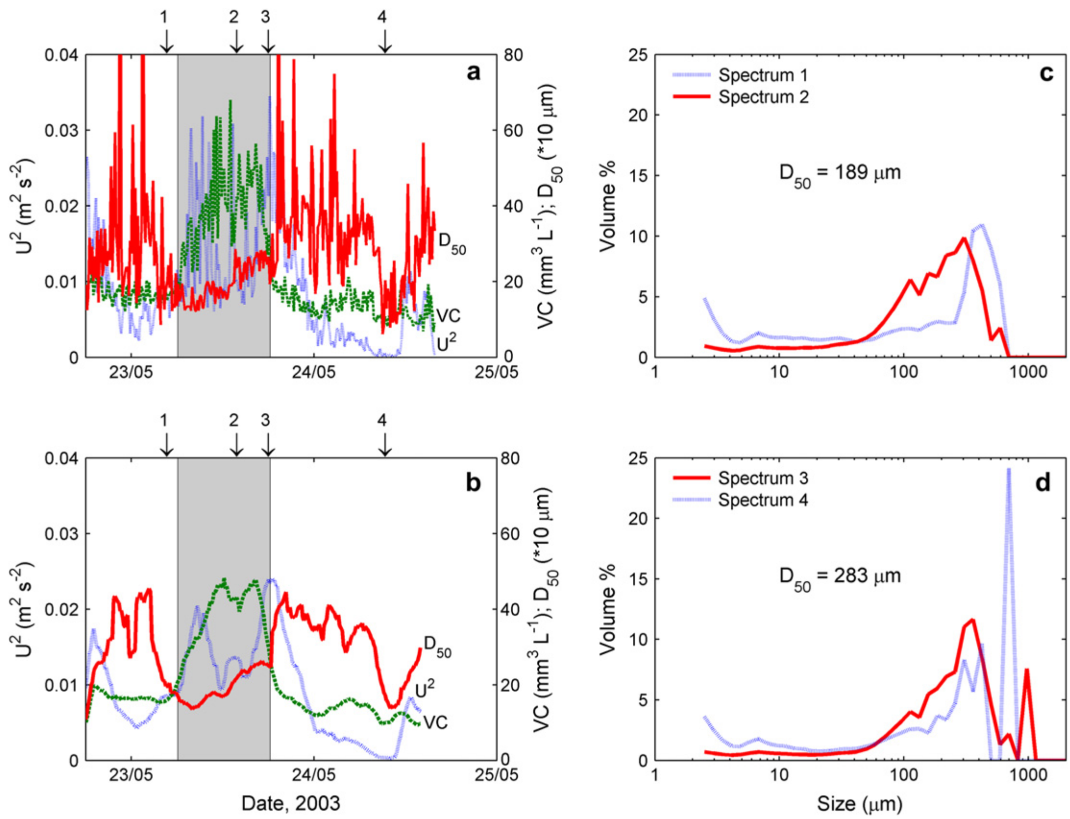

Fig. 2. (a) Temporal variability in median diameter (D_{50}, red solid line), volume concentration (VC, green dashed line) and the current velocity squared (U^2, blue dotted line). The timing and duration of the gale are indicated by the hatched area with generally low D_{50} and generally high VC and U^2. Note that VC and D_{50} are plotted on the same axis. The arrows marked 1–4 show when the size spectra in (c) and (d) were measured. (b) Same as (a) but with a 2-h moving average applied. (c) The two in situ particle size spectra corresponding to 1 and 2 in (a) and (b). Spectrum 1 is measured prior to the gale while spectrum 2 is measured during the gale. (d) The two in situ particle size spectra corresponding to 3 and 4 in (a) and (b). Spectrum 3 is measured during the gale while spectrum 4 is measured after the gale. Note similar D_{50} but different shape for the pairs of spectra in (c) and (d) and similar shape but different D_{50} for spectra 2 and 3 (during the gale).

two distributions with the same relative volume in microflocs. In one, the volume could be distributed evenly, whereas in the other, the volume distribution could have a distinct mode. Such a difference would indicate different particle dynamics, yet it would be overlooked. Furthermore, this division of mass offers no objective means for identifying when important changes in the particle size distribution occur. For example, during the Chienti deployment, microfloc volume as a percentage of the total suspended volume varies from 12 to 30%, with higher values occurring during resuspension (Mikkelsen et al., 2006). With this type of characterization, it is not clear how to define a particular percentage that marks a size distribution uniquely as a product of resuspension. This difficulty complicates the task of identifying and explaining predictable responses of the size distribution to environmental forcing by waves, currents, biological processes, etc. Entropy analysis may be able to address these problems.

Entropy analysis is a method for analyzing size spectra that makes no assumptions about the underlying shape of the spectra. This concept originates from information theory (Shannon, 1948). It evaluates the randomness of an event or a signal, and then either assigns that signal to a group that contains similar signals or places it in a new group. The method has been used successfully by Forrest and Clark (1989) and Woolfe et al. (1998, 2000) to discriminate geological facies in cases where traditional bivariate plots failed, but it has not been applied to in situ particle size spectra. This paper sets out to explore the usefulness of entropy analysis of in situ floc size spectra in the marine environment. In particular, it examines the ability of the method to identify and describe the distinct particle size distributions generated by the Chienti resuspension event.

1.1. Entropy analysis

In information theory, the concept of entropy is related to the randomness of an event or a signal. Essentially entropy links the information content of a signal to its randomness – if a signal has a high entropy (high randomness) the information content is low and vice versa. In particle size terms, this can be illustrated by considering a completely flat size spectrum, i.e. all volume (or mass) in the size spectrum occurs with the same frequency throughout the spectrum. This is essentially a random distribution of matter throughout the size spectrum, so a size spectrum with this shape has maximum entropy. Conversely, in a size spectrum where all particle volume or mass is found in only one bin there is no randomness of the distribution, so the entropy for such a spectrum is at a minimum. Therefore, a particle size spectrum can be characterized in terms of its entropy. For a particle size spectrum with n size bins, the entropy, E, is given as:

$$E = -\sum_{i=1}^{n} p_i \log p_i, \tag{1}$$

where p_i is the proportion of particles in size bin i (Shannon, 1948; Johnston and Semple, 1983). Note that when $p_i = 0$, $p_i \log p_i = 0$ (according to L'Hôspital's rule). The entropy can vary between a maximum value, E_{MAX} of $\log n$ when all $p_i = 1/n$ and a minimum value, E_{MIN}, of zero when $p_i = 1$ for exactly one of the bins $i = 1\ldots n$. The entropy is related to the information gain, I, which is also known as the inequality statistic, by the equation:

$$I = (\log n) - E \tag{2}$$

When E equals E_{MAX}, the proportion of particles is the same in all size bins, and I equals zero. As the value of I increases, the information content of the size spectrum increases.

With an ensemble of size spectra, the inequality statistic can be used to divide the spectra into groups. Optimal grouping maximizes the inequality between the groups and minimizes the inequality within the group, so the spectra in each group all have similar shapes, and the shapes of the spectra differ mainly between groups. The first step in grouping size spectra is to express the proportion of particles in each size bin of each size spectrum as proportions of the grand total (Johnston and Semple, 1983). For size distributions expressed as volume concentrations, the volume concentration in each size bin of each spectrum must be divided by the grand total volume concentration, defined as the sum of the volume concentration in all bins in all spectra:

$$Y_{ij} = \frac{\mathrm{VC}_{ij}}{\sum_{i=1}^{N} \sum_{j=1}^{J} \mathrm{VC}_{ij}}, \tag{3}$$

where N is the number of spectra, J is the number of size bins in each spectrum, VC_{ij} is the volume concentration in spectrum i, bin j and Y_{ij} is the proportion of the total volume concentration in spectrum i, bin j.

Following Johnston and Semple (1983), the total inequality for all spectra is then given as:

$$I = \sum_{j=1}^{J} Y_j \sum_{i=1}^{N} Y_i \log NY_i, \tag{4}$$

where $Y_j = \sum_{i=1}^{N} Y_{ij}$ and $Y_i = Y_{ij}/Y_j$.

In case the spectra have been divided into R groups, a measure of the efficiency of the grouping (in terms of maximising between-group inequality) can be obtained from the so-called R_{S} statistic (Johnston and Semple, 1983):

$$R_{\mathrm{S}} = (I_{\mathrm{B}}/I)100 \tag{5}$$

In Eq. (5) I_{B} is the between-group inequality, which is defined as:

$$I_{\mathrm{B}} = \sum_{j=1}^{J} Y_j \sum_{r=1}^{R} p_{jr} \log\left(\frac{p_{jr}}{N_r/N}\right), \tag{6}$$

where $p_{jr} = (\sum_{i\in r} Y_{ij})/Y_j$, and N_r is the number of spectra in group r of R. High R_{S} values indicate that the inequality is mostly related to differences between the groups and that the inequality within each group is low. In short, the spectra within each group have similar shapes, and the shapes of the spectra differ mainly between groups.

Unfortunately there is no way to predict in advance how the spectra should be grouped or how many groups are desirable. The only way to obtain a best grouping (simply defined as the best R_{S} statistic) is to perform all possible combinations of N spectra into R groups, compute the R_{S} statistic for each of the combinations and then choose the combination that yields the largest R_{S} statistic for that number of groups. This problem is well known from other grouping techniques such as, for example, principal component analysis, where the full set of principal components is as large as the original set of variables, but the vast majority of the variation usually can be explained by the first two to four principal components.

Johnston and Semple (1983) provided a FORTRAN routine that automatically arranges the data into a user-selected number of groups, and then shifts them between groups until an optimal grouping for that number of groups is found. Their routine was later adapted to QBASIC by Woolfe and Michibayashi (1995), who demonstrated how the entropy method could be used to group bottom sediment size spectra into meaningful sedimentological facies. Further work on the use of entropy analysis to discriminate between sedimentological facies has been presented by Woolfe (1995), Woolfe et al. (1998, 2000) and Orpin et al. (2004). Orpin and Kostylev (2006) demonstrated that entropy analysis was also useful in delineating ecological habitats on the Scotian Shelf off Nova Scotia, Canada.

2. Study site and methods

2.1. Study sites

Fieldwork was carried out as part of the EuroSTRATAFORM program funded by the US Office of Naval Research. One goal of the EuroSTRATAFORM program was to advance understanding of the transport and deposition of fine-grained sediment on the inner Adriatic shelf off the east coast of Italy (Fig. 1). The results presented here originate from fieldwork on the inner Adriatic shelf that took place in May/June 2003 off the mouth of the Chienti River.

On the inner Adriatic shelf, the circulation, transport, and deposition of suspended matter are substantially influenced by the Po River, which has a sediment discharge of the order of $13-20 \times 10^6$ tons/year and a freshwater discharge of the order of $1500\ \mathrm{m}^3/\mathrm{s}$, peaking up to $12\,000\ \mathrm{m}^3/\mathrm{s}$ during floods (Nelson, 1970; Milliman and Syvitski, 1992). The Chienti River further south has a sediment discharge of the order of 1.3×10^6 tons/year and substantially influences the local dispersal pattern of sediment (Milliman and Syvitski, 1992; Ravaioli et al., 2003). The dispersal of sediment and water is also influenced heavily by the regional wind climate as well as the overall circulation pattern in the western Adriatic, where the Western Adriatic Coastal Current (WACC) flows towards the south throughout the year (Orlic et al., 1992). The Chienti deployment took place within the WACC in a water depth of 12 m, which was less than 1000 m from shore.

2.2. In situ particle size and volume

In situ particle size spectra were obtained by use of the INSSECT (IN situ Size and SEttling Column Tripod; Mikkelsen et al., 2004). The INSSECT is equipped with a LISST-100 (Agrawal and Pottsmith, 2000) and a digital floc camera (DFC, described in detail by Mikkelsen et al., 2004). The DFC takes still pictures of the suspended particles by means of silhouette photography whereby the particles are lit from behind using an LED flash. The particles thus appear dark on a bright background. The field of view (FOV) is a $4 \times 4 \times 2.5$ cm slab of water, and the DFC is focused on the middle part of the slab. A small aperture setting and a bright light source ensure that all particles in the FOV are in focus. The LED flash strobes the DFC with a 20 μs pulse. This ensures that the particles in the image are ‘frozen’ and not blurred due to particle movement. The images are stored on an internal hard drive, capable of storing up to 1000 grey scale images with a size of 1024×1024 pixels in 256 grey scale values. The pixel size of the camera is 45 μm. In this study, nine coherent pixels were chosen as the minimum number of pixels to define a particle in an image, giving a minimum resolvable particle size of approximately 135 μm. During deployments the DFC was programmed to take a picture every 5 or 10 min depending on the length of the deployment. Upon recovery, the images from the DFC were offloaded to a PC and analyzed using a set of MATLAB image processing scripts yielding the volume distribution in logarithmically spaced size bins from 133 to 9900 μm.

The LISST-100 was programmed to measure at 4 Hz in a burst mode where every 10 measurements were averaged into one sample. Each sample was thus obtained at 0.4 Hz. For each burst, 10 samples were saved with an interval of 5 s between samples. The burst length was thus 50 s. The interval between individual bursts was 5 min. Upon recovery, the data were offloaded and analyzed according to standard LISST data analysis procedures (Agrawal and Pottsmith, 2000), yielding the volume distribution in logarithmically spaced size bins from 2.5 to 500 μm.

2.3. Merged size spectra

All LISST-100 volume spectra from each burst were averaged into one spectrum, which was then merged with its corresponding DFC particle volume spectrum according to the procedure described by Mikkelsen et al. (2005). This procedure takes advantage of the fact that the LISST-100 and the DFC overlap in the 133–500 μm size range. The shape of the size spectra from the two instruments in these overlapping bins is compared and usually they are found to be offset but with the same shape (Mikkelsen et al., 2005; Fig. 3). Based on the offset in the eight overlapping size classes, a conversion factor is found that collapses the overlapping part of the LISST-100 spectrum onto the overlapping part of the DFC spectrum (Fig. 3). The entire LISST-100 size spectrum is then multiplied by this conversion factor, and the two spectra can be combined. This produces an in situ size spectrum covering particles from 2.5 to 9900 μm (Fig. 3), with the upper size limit being defined by the camera design. Mikkelsen et al. (2005) demonstrated that this is a robust method of obtaining full in situ particle size spectra, even when ‘rising tails’ (Mikkelsen et al., 2005) exist in the LISST-100 spectra. From the full in situ volume distribution the particle diameters D_{50} and D_{25} were then computed where D_{50} is the median particle diameter, and D_{25} is the upper quartile diameter for the full volume distribution (see Mikkelsen et al., 2005 for details).

2.4. Entropy analysis

A Matlab translation of the QBASIC routine of Woolfe and Michibayashi (1995) was used to perform the grouping of in situ size spectra. Woolfe and Michibayashi (1995) provided a test data set with their routine, and the Matlab translated routine used here yielded the same output as reported by Woolfe and Michibayashi (1995).

3. Results

The spectra from off the Chienti River ($n = 276$) were divided into two to five groups using the entropy method and the temporal variation in group occurrence plotted together with the variation in D_{50} during the deployment (Fig. 4a–d). A short-lived gale passed through the area during the deployment, causing an increase in the volume concentration (VC) and stress, here expressed as current velocity squared (U^2) (Fig. 2). Size spectra measured during the gale all fall in one group when the spectra are divided into two, three or four groups and in two groups when the spectra are divided into five groups. Fig. 4e–h shows the average size spectrum for each of the groups and Table 1 lists D_{50} for the average size spectrum for each group.

Fig. 4a–c and Table 1 demonstrate that the size spectra obtained during the gale have the same average size spectrum and D_{50} (186 μm) if the spectra are divided into two to four groups. If the spectra are divided into five groups, the spectra measured during the gale fall into two groups with a median diameter of, respectively, 158 and 236 μm (Table 1). Table 1 also shows that the total number of individual size spectra that fall in groups occurring during the gale is almost constant (between 76 and 83 spectra), regardless of how many groups are chosen.

Fig. 4e–h shows the average size spectra for each group when all spectra are divided into two to five groups. Generally, the shapes of the average spectra are rather flat and similar for particle sizes up to 30–40 μm. The average spectra belonging

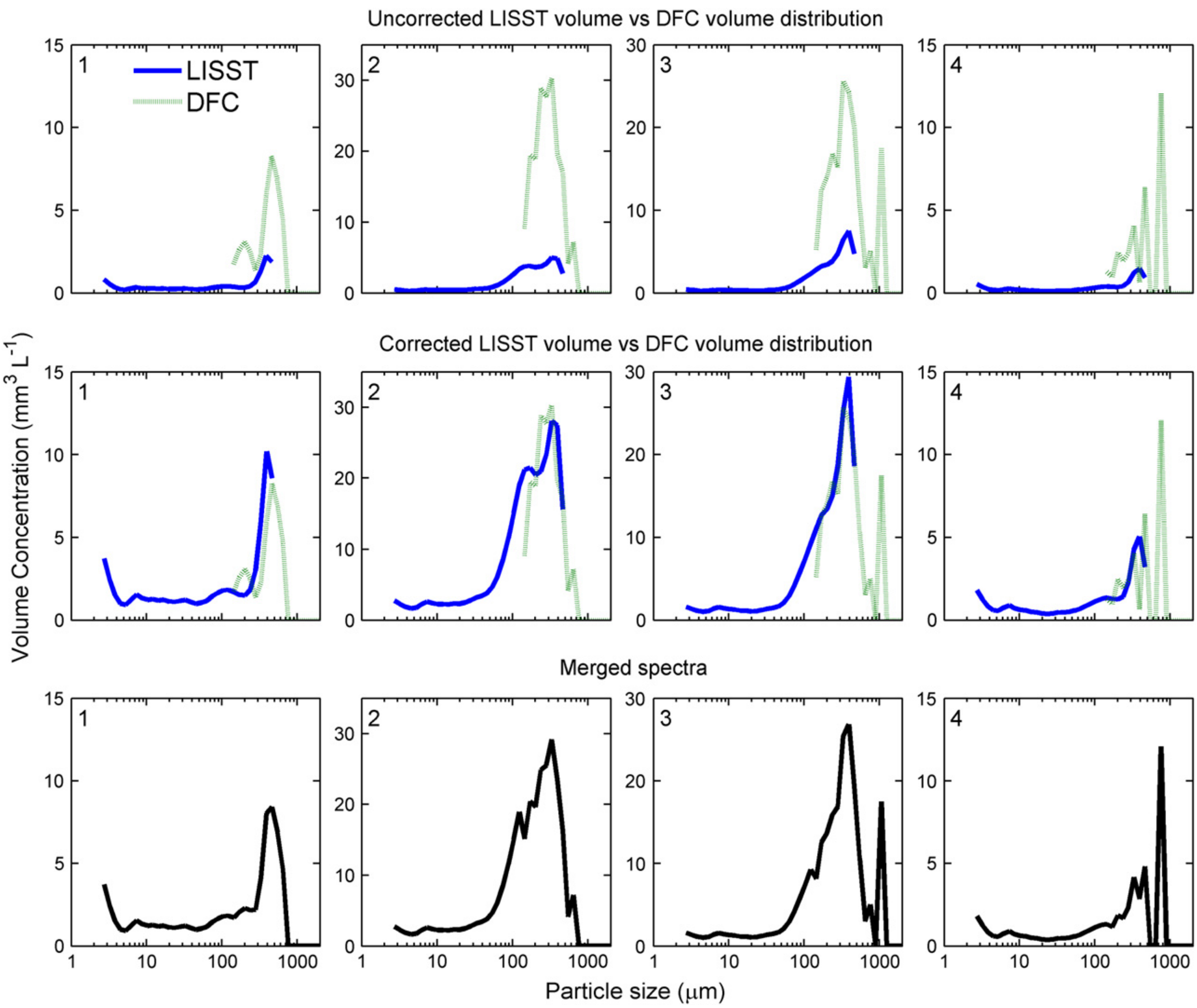

Fig. 3. Four examples of merging LISST-100 and DFC in situ size spectra. Top row shows the absolute volume distributions from the LISST and DFC at four times during the deployment (cf. arrows 1–4 in Fig. 2). Middle row shows how the LISST spectra have the same shape as the DFC spectra in the region of overlap (133–500 μm) after the volume in the LISST spectra has been corrected (see Mikkelsen et al. (2005) and text for details). Bottom row shows the merged spectra (cf. Fig. 2).

to the group (or groups) occurring during the gale are generally enriched with particles in the 40–300 μm range when compared to the average spectra from non-gale groups. Generally, the average spectra for the gale groups have a convex shape for the part of the spectra between 40 μm and the mode, while they have a concave shape for the part of the spectra larger than the mode. The average spectra from non-gale groups are all concave on the fine side of the mode, but exhibit both concave and convex shapes on the coarse side of the mode.

Fig. 5 shows the efficiency of the grouping. When considering all the spectra measured during the Chienti deployment, no particular shape or visually obvious grouping is apparent. However, dividing the spectra into two to five groups demonstrates that the average spectrum from each group captures much of the variability among the individual size spectra, especially for the spectra observed during the gale. This can be quantified via the R_S statistic in Table 1, demonstrating that up to 47% of the variability among the size spectra can be explained by just five groups (hence five average spectra).

4. Discussion

It is apparent from Fig. 4a–e that D_{50} decreased rapidly to approximately 135 μm at the on-set of the gale, and then slowly increased during the gale to approximately 280 μm towards the end of the gale. Changes in floc size can occur due to five processes: erosion, deposition, advection, floc break-up and flocculation and their influence on the observed variation in floc size during the gale will be discussed in the following paragraphs. Subsequently the results of the entropy analysis will be used to elucidate in more detail the likely processes going on.

Erosion of particles from the bed could cause the observed slow increase in D_{50} if the particles being eroded during the gale became larger as the gale progressed. The bed sediment off the Chienti site is fine sand with a mean grain size around 100 μm (Passega et al., 1967; George et al., in press). Thus, as D_{50} during the gale is larger (135–280 μm) than the grain size of the bed sediment, the slow increase in D_{50} cannot be related

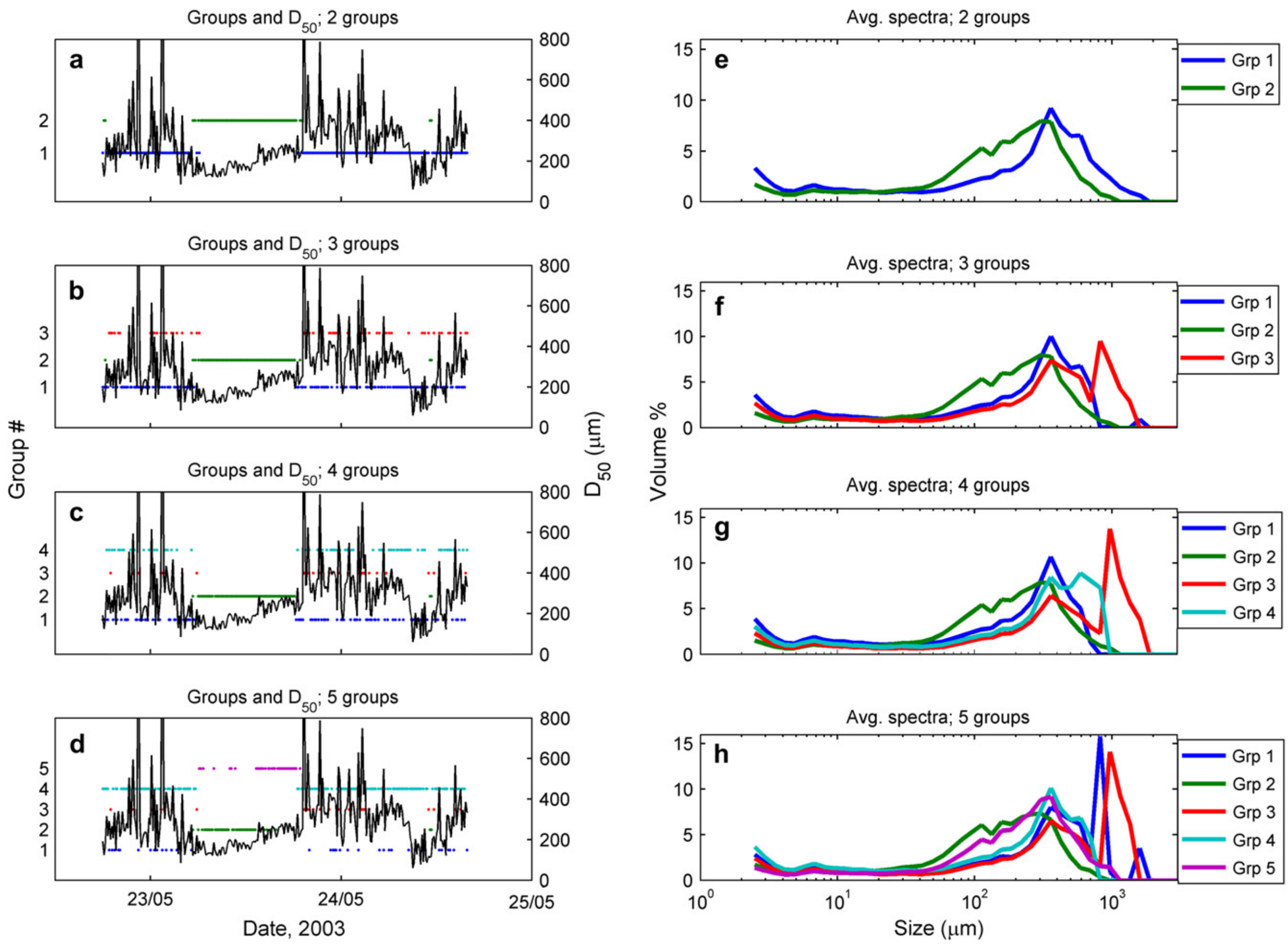

Fig. 4. Results obtained by grouping the observed in situ size spectra using the entropy method. (a–d) Temporal variation in D_{50} (full line) and group occurrence (horizontal dotted lines) during the Chienti deployment for two to five groups. Each dot indicates a size spectrum and shows where it belongs in time as well as its group affinity. For example, in (a) spectra belonging to group 1 occur before or after the gale, but not during the gale whereas spectra belonging to group 2 occur almost exclusively during the gale. (e–h) Average size spectrum for each group when the spectra are divided into two to five groups.

to erosion of single (sand) grains from the bed. Floc erosion has been observed with in situ video cameras by, e.g. Thomsen and Gust (2000) who reported diameters of eroded flocs from 200 µm to more than 2000 µm. If flocs of this size were eroded from the bed they would show up in the merged in situ size spectra as peaks in the >200 µm size bins. This was indeed the case (cf. spectrum three in Fig. 2d) but the absolute as well as the relative volume of these large flocs was smaller during the gale than before and after the gale (Mikkelsen et al., 2006). Consequently, floc erosion cannot have caused the general increase in D_{50} observed during the gale. Summarizing, single grain and floc erosion are unlikely to have influenced the observed variation in D_{50}.

Deposition of particles would normally cause a decrease in D_{50} as the largest flocs would settle out first due to the generally higher settling velocities of large flocs (Hill et al., 1998; Mikkelsen et al., in press). Thus, deposition cannot explain the increase in D_{50} during the gale. It should be generally acknowledged, however, that the influence of erosion as well as deposition on D_{50} is generally poorly documented in the literature. In order to properly constrain this, simultaneous vertical point-measurements of the in situ size distribution together

Table 1
Median diameters for the average spectra from the groups created when the size spectra from Chienti are divided into two to five groups. The numbers in bold are the median diameters of the average spectra for the group(s) occurring during the gale. Numbers in parentheses indicate the number of individual spectra in each group, out of the total 276 spectra. Also shown is the R_S statistic for two to five groups (see text for details)

	Median diameter for group # (µm) (*n*)					R_S (%)
Groups created	1	2	3	4	5	
2	296 (193)	**186** (83)				25
3	256 (134)	**186** (79)	378 (63)			36
4	217 (96)	**187** (76)	447 (32)	336 (72)		44
5	366 (35)	**158** (44)	423 (29)	249 (133)	**236** (35)	47

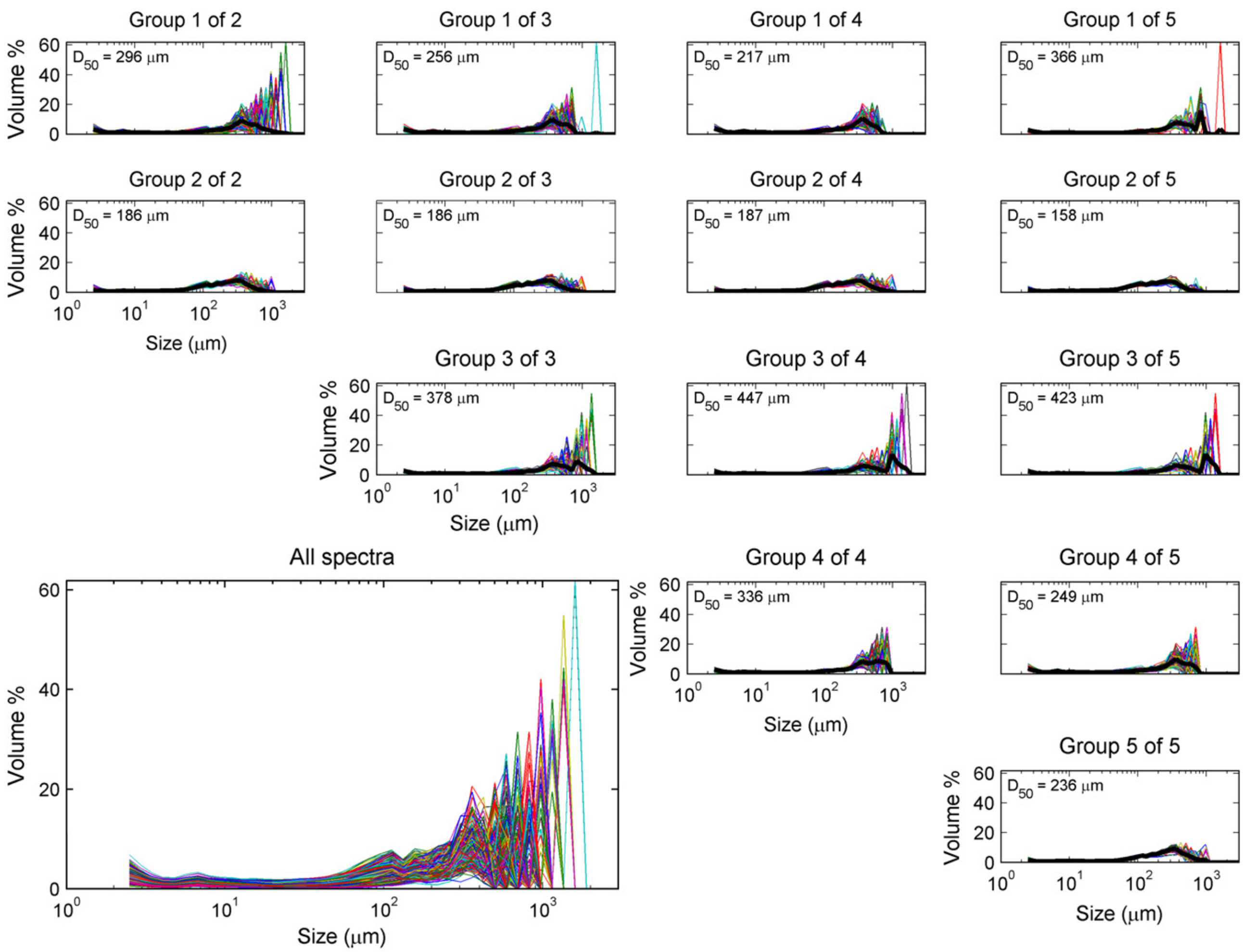

Fig. 5. Comparison of the groups obtained when grouping the observed in situ size spectra using the entropy method. All observed spectra (276 in total) are shown in the bottom left plot. It is seen that no particular groups can be defined by the naked eye. In the four columns all spectra in a group is plotted together with the average group spectrum (black line) for all groups created when the observed spectra are divided into two to five groups.

with measurements of associated turbulence and in situ settling velocity would be necessary.

The influence of advection on in situ floc size distribution and D_{50} can only be constrained if measurements take place simultaneously in at least two places relatively close to each other, e.g. two tripods spaced a few hundred metres to a few kilometres apart. Additionally, the texture of the bed sediment on the study sites should be similar in order to minimize the effect of erosion of bed sediment with varying grain size on D_{50}. No such simultaneous measurements of in situ size were carried out during the EuroSTRATAFORM program, but the potential influence of advection on changes in D_{50} can be assessed in other ways. Hill et al. (2000) demonstrated that floc sizes during storm conditions in river plumes on the continental shelf are constant with no obvious spatial gradient as long as suspended sediment concentrations are below a few hundred milligrams per litre. Consequently, for the results presented here advection can be ruled out as a major contributor to the observed increase in D_{50} during the gale.

Floc break-up causes a decrease in D_{50} and can thus explain the decrease in D_{50} observed with the on-set of the gale. However, D_{50} increased during the gale, which cannot be explained by floc break-up.

This leaves flocculation as the most likely explanation for the steady increase in D_{50} observed during the gale and it suggests that the flocs were growing under stress. The shape of the average size spectra on the fine and coarse side of the mode differed for the groups that were observed during the gale and for the non-gale groups. The shape of the spectra for the gale groups tended to be convex to the fine side and concave to the coarse side of the mode (Fig. 4e–h). Krishnappan and Marsalek (2005) carried out a series of flocculation experiments in a rotating flume and modelled the floc size distribution under stress as flocs were growing towards a steady-state equilibrium size distribution and D_{50}. They did not comment on the shape of the size spectra, but from their observation and modelling effort it appears that the shape of the floc size spectrum initially, as flocs start to grow, is convex to the fine side and concave to the coarse side of the mode (figures 8.6 and 8.10 in Krishnappan and Marsalek, 2005). When steady state has been reached, and D_{50} is no longer increasing, the size distribution is distinctly concave to the fine side of the mode and either concave or convex to the coarse side of the mode (figures 8.9 and 8.13 in Krishnappan and Marsalek, 2005). Similarly, Biggs and Lant (2000) presented floc size spectra observed during a sludge flocculation experiment showing that the equilibrium size spectra were highly concave on either side of the mode. The observations presented here thus seem to tailor well with the size spectra presented by Krishnappan and Marsalek (2005) and Biggs and Lant (2000). If flocs are growing under stress, growth must occur mainly from the fine side of the mode, gradually 'removing' small flocs by moving them towards the mode due to flocculation. Thereby the fine side of the mode would become depleted and change shape, as the figures presented by Krishnappan and Marsalek (2005) also suggest.

The total number of groups the spectra should be divided into is a moot point (Orpin and Kostylev, 2006). The R_S statistic automatically increases as the number of groups is increased and is thus not, by itself, suitable to determine the optimum number of groups. However, it has been used to compute a test statistic, the Calinski–Harabasz pseudo F-test, which proved to be more useful for determining the optimum number of groups when the number of size bins was reduced to only three to six bins (Orpin and Kostylev, 2006). Orpin and Kostylev (2006) explained this as being due to an increase of within-group variability when the number of size bins increased, irrespective of the total number of spectra. Forrest and Clark (1989) defined a statistically optimum grouping when the growth rate of between-group entropy decreases significantly with the addition of further groups. A plot of R_S versus number of groups for the data presented here shows a decrease in the growth rate of R_S up to five groups (Fig. 6). Adding a sixth group causes an increase in R_S of more than 10%, suggesting that the optimum number of groups could be six or even more. However, an inspection of the additional group created when moving from five to six groups revealed that the new group contained only six spectra, all related to occasions where the DFC images contained a very large particle, which caused a dramatic increase in D_{50}. Such random occurrences of single very large particles are of questionable significance, as they are not indicative of the prevailing forcing conditions. Thus, the spectra from this deployment were divided into a maximum of five groups.

Increasing the number of groups from two to five does not cause any overall change in the shape of the gale or non-gale average spectra (Figs. 4 and 5). However, details emerge as the number of groups is increased. For example, dividing the spectra into five groups indicates that only groups 2 and 5 were present during the gale. Group 5 mainly occurred in the latter half of this period contemporaneously with a steady increase in floc size (Fig. 4d). Overlaying the average spectra for groups 2 and 5 and displacing the group 2 average spectrum two size bins (0.5 ∅) towards the coarse end of the spectrum (Fig. 7) reveals that the spectra essentially have the same shape. The influences from erosion, advection, deposition and dis-aggregation on the size spectra were discussed above, so the observed change in the spectra suggests that during the period of steady floc growth (groups 2 and 5) the flocs generally grew by adding single grains or small flocs from the fine end of the spectrum to all bins in the coarse end of the spectrum. Otherwise it is difficult to explain the similar shape between the group 2 and 5 spectra.

Growth of larger flocs by scavenging of small flocs and single grains is not evident during the occurrence of group 3 and 4 spectra when the stress began to decline. As soon as the stress began to relax the spectra fell into group 4, which is characterized by a well-developed shoulder on the coarse side of the mode in the average spectrum. Fifty minutes later group 3

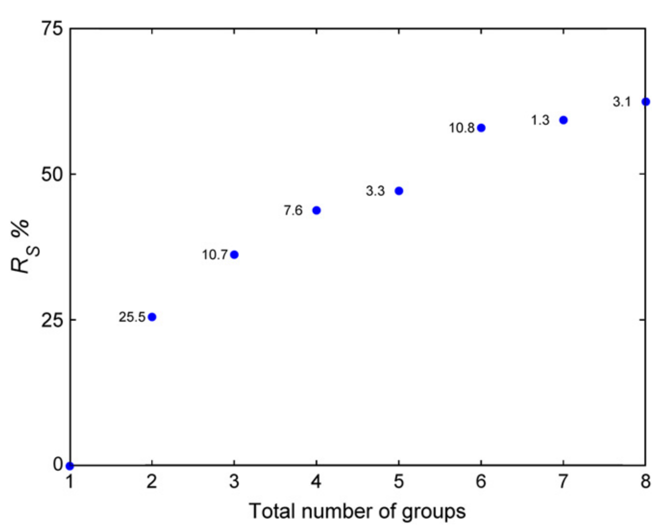

Fig. 6. Plot of total groups versus R_S. The data points indicate the R_S value for a given total number of groups. For example, when the 276 spectra are divided into three groups R_S is 36.2%, indicating that the three average spectra for the three groups explain 36.2% of the variability in the shape of all 276 spectra. The numbers to the left of the data points indicate the increase in R_S when adding another group. For example, 10.7 at three groups indicate that the R_S increased 10.7% when the total number of groups was increased from two to three.

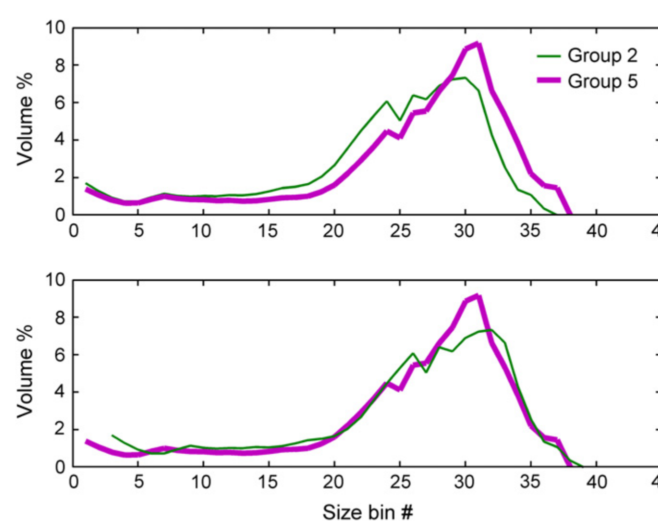

Fig. 7. Spectra from off the Chienti River showing the average spectra for groups 2 and 3. It is seen that the spectra generally have the same shape, but that group 3 spectra (occurring during re-flocculation) simply have been displaced two size bins towards the larger sizes.

spectra began to appear with their characteristic second coarse mode centered at 970 μm. This suggests that flocs grew rapidly by floc collision and adhesion once the stress relaxed, and that they did not solely grow by adding single grains and small flocs to already existing flocs. If the flocs had continued to grow by adding on single grains to existing flocs, no second modes should have appeared (Fig. 7). The observations indicate that floc growth during high stress occurs by single grains and microflocs adhering to existing particles in almost all size classes, thereby shifting the entire spectrum towards coarser sizes. During periods of low stress, floc formation occurs mainly by interfloc collisions, creating new coarser modes in the size spectra on time-scales of roughly one hour.

These findings are in agreement with Mikkelsen et al. (2006). They reported that when stress increased, the volume occupied by macroflocs decreased while the volume occupied by microflocs increased. This is consistent with the change in the average spectra from groups 1, 3 and 4 (typically bi-modal and a large D_{50}) to groups 2 and 5 (typically unimodal and the smallest D_{50}). The entropy method objectively identifies the distinct spectra associated with floc growth and resuspension, and it allows for a more detailed examination of changes in the size spectra during varying forcing conditions. For these reasons, the method should be considered for any assessment of particle size variability.

In situ size spectra during periods of floc growth under high stress are different from spectra during periods of growth under low stress (Figs. 2, 4 and 5). In general, this finding supports the hypothesis that the in situ size spectrum is a function of the environmental conditions (e.g. turbulence, biological activity, suspended matter concentration) close to the time of measurement. If so, all spectra in a group are the result of forcing conditions varying within a certain range. Consequently, it may be possible to build a library of average in situ size spectra based on empirical observations, with each average spectrum being representative of a certain range of variation in the forcing conditions. Such a library could be used to estimate the in situ size spectrum of suspended particulate matter without actually modelling the spectrum. Based on actual measurements or model outputs of the forcing conditions at a given time a lookup in the library would provide the average size spectrum for these conditions. Recently it has been shown that the in situ floc density and settling velocity can be estimated from the in situ floc size distribution when the density and median diameter of the primary particles are known or can be estimated (Khelifa and Hill, 2006). Mikkelsen et al. (2005) used the results of Khelifa and Hill (2006) to compute the mass size distribution and subsequently the in situ floc fraction (the fraction by weight of the suspended sediment that exists as part of flocs). Thus, the average floc density, floc settling velocity and floc fraction could be computed from the average spectrum. Also optical properties related to the concentration of fine-grained particles could be computed from the average spectrum. To assess the efficacy of such an approach requires longer time series of particle size distribution, during which forcing conditions vary markedly. Additionally, variability in space might be analyzed with entropy analysis as well.

Other types of spectra may benefit from the grouping potential of the entropy method. Settling velocity and settling flux spectra have been presented by, for example, Fennessy et al. (1997), Jago and Jones (1998), and Jones et al. (1998). It could be hypothesized that the shape of these spectra would be controlled by the same factors that control the shape of the in situ size spectra. These settling spectra could be grouped and the relationship of the groups to the forcing conditions could be examined. Potentially this could assist in estimates of settling fluxes to the seabed. Finally, it might also be worthwhile to attempt grouping of completely different types of spectra, such as remote sensing spectra (Feng et al., 2005) or energy spectra.

5. Conclusions

By using the entropy method described by Johnston and Semple (1983) and Forrest and Clark (1989), in situ particle size spectra can be grouped to obtain useful information regarding environmental controls on particle size. Applying the method to in situ size spectra from the Adriatic Sea revealed that floc growth during high stress occurs by slow growth in all size bins, simply shifting the size spectrum towards larger sizes. In contrast, floc growth during low stress occurs on a time-scale of 10s of minutes, rapidly producing bi-modal spectra with the largest flocs of the order of 1000 μm. These results are in accordance with model and flume results presented by Krishnappan and Marsalek (2005). It is argued that the shape of the in situ size spectrum must be a function of a limited number of variables, chief amongst them being probably turbulence, biological 'stickiness' and suspended matter concentration. Therefore, a group of size spectra that all have roughly the same shape should be indicative of these variables varying within a certain limited range. The in situ size spectra in a particular body of water perhaps can be reduced to a handful of groups, each typical of the forcing conditions varying within a certain range. Thus, a library of entropy groups could be built for a particular region and subsequently the average shape of the spectrum in that region could be estimated from measurements of the forcing parameters. This strategy enables computation of average floc effective density, floc settling velocity, and floc fraction. It is also suggested that the entropy analysis might be able to reveal if changes in floc size are mainly due to settling, resuspension or advection. Finally, grouping other types of spectra might prove beneficial.

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