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Biogeosciences Discussions

Interactive comment on "Optics and remote sensing of Bahamian carbonate sediment whitings and potential relationship to wind-driven Langmuir circulation" *by* H. M. Dierssen et al.

H. M. Dierssen et al.

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We would like to thank our reviewers for the time and attention they applied to this manuscript. We have incorporated all of their comments into the final version of the manuscript and feel that their input has made this a more readable and comprehensive paper.

Response to reviewer 1

There is not enough description about Langmuir cells in the paper and a few vital characteristics are missed out. Firstly the orientation of Langmuir cells is parallel to the wind direction (indeed wind direction as far as I can see is not mentioned in the paper). In the northern hemisphere their orientation is 15_ to the right of the wind direction.

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Interactive Discussion
Discussion Paper

The action of Langmuir circulation is to setup helical rolls within the water column and this causes horizontal streaks on the surface where material (and debris) accumulates.

We have amplified the introductory material on Langmuir in order to make the reader more familiar with the topic. Thorpe 2004 (Ann. Rev. Fluid Mech. 36:55-79) presents a nice overview of Langmuir Circulation and the substantial advances in modeling and observations that have led to a “radical change in understanding the phenomena.” The last two paragraphs of the introduction now read:

Here, we present some of the most comprehensive measurements of inherent optical properties within a sediment whiting event and propose that wind-driven Langmuir cells (Langmuir 1938) reaching the full-depth of the water column (i.e., “Supercells”, Garget et al. 2004) may represent a plausible mechanism for sediment resuspension and subsequent whiting formation. Langmuir cells at scales of 2 m to 1 km are now generally accepted to be the result of the interaction of the Stokes drift induced by surface waves and the vertical shear in turbulent fluid (Thorpe 2004). Langmuir circulation is commonly characterized by three-dimensional rotating cells that form surface convergence at the boundary of counter-rotating cells (Weller, et al., 1985) that can be visibly observed as windrows of buoyant material including algae, plankton, or bubbles aligned parallel to the winds (Monahan and Mingzhi, 1990). However, a cell is neither steady nor uniformly spaced, but rather interacts with itself and other cells (Tejada-Martinez and Grosch, 2007). While much research has focused on upper-ocean mixing, Langmuir circulation has only recently been recognized as a possible mechanism shaping seafloor processes. In shallow water, the vertical scale of Langmuir “supercells” can reach the full depth of the water column (Faller, 1971; Gargett, et al., 2004); thereby, potentially resuspending sediment, altering benthic constituents, and sculpting the seafloor. Along the eastern arm of the Bahama Banks, we observed Langmuir cells manifested as organized windrows of benthic macroalgae Colpomenia sp. that may have transported significant biomass off the shelf into deep water (Dierssen et al. 2009). The downward velocities of such su-

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percells exceed the upward velocities (>6 cm s-1) and peak several meters below the sea surface. Sediment transport due to Langmuir supercells is distinct from that associated with surface waves because of the different vertical length scales. Near-bottom turbulence due to surface waves causes sediment resuspension only within a thin wave boundary layer extending tens of centimetres from the seafloor (Gargett, et al., 2004; Grant, 1986). In contrast, Langmuir supercells create a mechanism whereby sediment can be moved out of the slow near-bottom flow and mixed throughout the water column. Hence, Langmuir circulation can play a dominant role in sediment dynamics in shallow environments, such as proposed here.

For Langmuir cells to be postulated as a plausible explanation, evidence is required that there was indeed regular spacing (and give magnitude) between the whitings with bluer water in between. As far as I can see the only evidence of this were the MODIS Aqua images and the periodicity in the inherent optical property data.

This is point deserves a bit more clarification in the paper. MODIS imagery does not have the spatial resolution to distinguish these small scale features. The visible manifestation of Langmuir was also not readily detectable with the human eye, which is not always the best discriminator of small changes in white. We have amplified the discussion as follows:

The visible manifestation of Langmuir cells as defined windrows was not readily detected from the course spatial scale of the MODIS imagery, nor was it evident from our casual observations with the unaided human eye. However, regular periodicity in the optical measurements (Fig. 4) indicated the presence of alternating patches of more and less turbid water (i.e., regularly fluctuating cp and bbp) that may give whitings the visible “roiling” nature that has been attributed to past whitings (Shinn et al. 1989). Such periodicity was not evident in any other station sampled during this cruise and was not due to vertical movement of the profiling package, which remained at a fixed depth of 2.8 + 0.047 m throughout the duration of the time series. We were unable to estimate the potential size of Langmuir cells from the periodicity mea-

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surements because no ancillary current measurements were obtained to differentiate the various components of the velocity field and the expected period of cell crossing. Our optical in situ data were obtained on an anchored ship that might have had lateral movement across cells. However, we note that the observed periodicity indicated patches of fluctuating turbidity on spatial scales that could be produced from regular rows of Langmuir cells penetrating the full 5-m water column. The fine-grained sediments common to the Andros region (Fig. 2) can stay suspended in the water column for considerable time and the presence of defined windrows will become more and more obscured over time. Hence, rather than producing clearly discernable windrows, Langmuir cells could produce mixed suspensions of fine aragonite mud throughout the water column.

I agree with the authors that Langmuir is more plausible than fish activity and tidal bursting, however straightforward wind driven mixing is also consistent with the pattern observed, as is possible internal wave breaking (see da Silva et al., 2002, GRL, DOI: 10.1029/2001GL013888 although unfortunately I am not familiar with the complex physics and bathymetry around the Bahamas!)

We also have a paper describing remotely detected chlorophyll patches (red tides) in relation to internal waves in Monterey Bay (Ryan, J., et al. 2005, Oceanography 18: 246-255). Physical oceanographers have long puzzled over the presence of whitings along this shallow water bank, but it hasn’t been consistent with traditional mechanisms or current measurements. We have modified the following paragraph in the paper to better discuss why Langmuir may be plausible.

First, Langmuir cells reaching the full extent of a 5-m depth water column were visually observed earlier in March 2004 on the eastern Exuma region of the Bahamas as regular rows of the benthic algae, Colpomenia sp., concentrated on the seafloor (Dierssen et al., 2009). Moreover, Langmuir supercells have previously been associated with resuspended sediments off the western Atlantic shelf in the LEO-15 site (Gargett et al., 2004). Langmuir cells serve to homogenize vertical velocity throughout the water

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column (Tejada-Martinez and Grosch, 2007) and could serve to resuspend sediment from near-bottom flows up throughout the water column (Gargett et al., 2004). Current velocities required to resuspend the fine aragonite muds on Andros would be less than that required to suspend larger-grained sediments common to other parts of the Bahamas. Although not measured here, previous research using an underwater flume indicates that currents in excess of 20 cm s-1 are necessary to erode and suspend bottom sediment from the region west of Andros Island (Shinn et al., 1989). Compared to other types of wind-driven turbulence (e.g., Couette turbulence), Langmuir cells produce maximum turbulent flow 3-10 times greater in all fluctuating velocity components and significant turbulent kinetic energy in near-bottom waters (Tejada-Martinez and Grosch, 2007) .

For Langmuir cells to be setup there also needs to be stability in the direction and strength of the wind. The wind data in the manuscript leaves a little to be desired; although several stations are mentioned the wind data from Nassau airport is used which is some 160 km to the east of the in situ stations. As the authors will be aware considerable variability in wind strength and direction is often observed around islands.

In an ideal world, we would have appreciated having continuous, long-term wind records near the study site to measure the strength and consistency of winds at the site. We have now seen Langmuir form in many shallow water environments (Florida Bay) and believe that the structure of these waters is ideal for such formation. Thorpe et al. 2004 writes that streaks of foam or other floating material are present in much lower winds and are almost always evident at some scale when there is material on the water surface to make patterns visible. The forces that shape Langmuir are complex. Winds were measured aboard the vessel, but these are not at the standard 10 m height required for modeling purposes. We added the following sentence to the beginning of the methods.

Winds measured aboard the vessel were 5.7 m s-1 predominantly from the west-northwest (291o).

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The Inherent Optical Property data were well explained, although in a highly scattering medium possibly some of the corrections to the ac-9 data would have been invalidated. The authors say in line 10 of p4781 that the "proportional (correction) method was inaccurate". How was the inaccuracy determined?

Probably for the reasons mentioned above (highly scattering), the proportional method would produce spectral profiles that sometimes took out too much signal at green wavelengths (smile type spectrum).

I also remain unconvinced about the accuracy of ac-9 determined chlorophyll concentration. Even fluorometrically determined chlorophylls would have given additional supporting evidence.

Yes, there are many uncertainties in estimating chlorophyll with an ac-9 measurement. However, it provides an approximation that is not central to the main hypotheses in the paper. We would like to use this study as a spring board to conduct further investigations that will elucidate how carbonate precipitation does occur on these banks (via precipitation on the particles or some via microbial processes) and further elucidate the mechanisms of Langmuir circulation in this region. A sentence was added:

We note that this approach is only meant to provide an indicator of chlorophyll concentrations.

The periodicity of the VSF data was one of the supporting evidences for Langmuir circulation. However my colleagues have observed, admittedly in some of our older instruments, that there is a marked periodicity in the data even when used in the laboratory to observe well mixed polystyrene beads in a bucket of milliQ. This behaviour we have attributed to the electronics of the instrument. It might be worth checking your own instrumentation back in the laboratory to see if you get the same response.

We note that this periodity of 40 s intervals and the general variability during the time series was not observed at any other station during the cruise where the ac-9 time

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series were consistently flat and stable, as shown in the example stations in Fig. 4. Moreover, high variability and periodicity was also evident in a completely independent instrument, the ECO-VSF, which produced the backscattering data shown in Fig 4C.

Response to Reviewer #2.

Page 4781, line17-19. "Measurements...(Sullivan et al 2005)." This isn’t a sentence. Given the rest is so well written, it must have been a typo. (or they are checking if I am was still paying attention)

Oops  This was revised.

The ECO-VSF (WET Labs) provided backscattering measurements at three angles (100°, 125°, and 150°) and three wavelengths (470, 532, and 650 nm). There data were corrected for light attenuation effects using concurrent ac-9 data and extrapolated from 90-180° using a third-order polynomial (Sullivan et al., 2005).

Same page, line 26, isn’t it more proper to add "coefficient", such as "specific absorption coefficient".

Done.

Page 4782, line 25. Some mention should be made of the timing between the insitu data and the MODIS image (do you exclude data over xx time from the image. how simultaneous were the ground truth and satellite data?).

Add to methods

Clear sky images were available on 6, 16, 18, 22, 27, and 30 March, 2004. The whiting was encountered in the field on 28 March, 2004 and compared to imagery collected one day prior (27 March, 2004).

In order account for error in the atmospheric correction, a single linear correction (slope and offset) was made to the entire image by comparing Rrs derived from the MODIS sensor with a selection of in situ measurements from selected stations (˜6) that were

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spatially consistent over kilometre scales and presumed to be relatively stable in water column optical properties over the course of the study.

Added to Fig. Legend The whiting was encountered in the field one day later on 28 March, 2004.

Page 4783, line 24. The reference to Fig 1b is sort of misleading here (I read this and went to the figure expecting to see a picture of the instrument package.

This was edited to read:

The water appeared turbid and chalky throughout the 5.3 m water column, as assessed by divers„ and the whiting persisted for tens of square kilometres.

Page 4785, line 12 and around. In various places in the paper it is mentioned that these whitings consist of aragonite particles, and in one place it even talks about the size. In another place it discusses the size of the sediment, which is argued as the source of the whiting. With all of this, how is it relevant at all to determine the size distribution as a Junge distribution slope (from a analysis which depends on sphericity and junge distribution) and go even farther to try to get to an index of refraction? I think this is a large, unjustified stretch. It is reasonable to say that the bbtilda is high, consistent with the waters having aragonite minerals (which you give the index of refraction of).

Yes, we agree this was a bit of a stretch, even with the caveats discussed in the original version, and the text has been revised to read:

An estimated bulk index of refraction could theoretically be estimated from approximations of the slope of the particle size distribution (Boss et al., 2001) and the particulate backscattering ratio (Twardowski et al. 2001). Such an approach was not applied here because particles within a whiting may not be spherical (Shinn et al., 1989) and the particle size distribution may not be strictly Jungian. However, the high particulate backscattering ratio is consistent with a water column dominated by aragonite minerals with a high index of refraction of 1.22 relative to water (i.e., 1.632-1.633 in its dry state;

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Aas, 1996).

Page 4791, line 25... might be more proper to reference Slade somehow, who had given the paper at OO.

Page 4793, top... are there any profiles of the water column?

No profiles were conducted because the water was shallow (˜5 m). In retrospect, it would have been nice to have one or two profiles before we did the time series. In the first paragraph of the methods we added the sentence.

The instrument package was not profiled over the ˜5 m water column.

Response to Editor Report

Aragonite and calcite are bi-refringent. How does that affect your interpretation?

None of the data were collected with polarized instruments and hence the birefringent properties of aragonite should not directly influence this analysis. From my understanding, birefringent materials are typically very dense and contribute highly to backscattering, as observed here. However, it would be very interesting to conduct further analyses in the lab and field using polarized filters on the instruments, including a full volume scattering meter, to further elucidate the optical properties of the suspended material.

Interactive comment on Biogeosciences Discuss., 5, 4777, 2008.