Wind Rows And Whitings: Unique Bio-Optical Phenomenon in the Bahamas Banks

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ABSTRACT

The Bahamas Banks, one of the largest optically shallow banks in the world, play an important role in the dynamics of carbon cycling through seagrass and dissolution of the underlying carbonate sediment in which the plants are rooted. However, these expansive tropical banks also produce some of the most unusual bio-optical phenomena on the planet. On a recent 3-week research cruise across the Bahamas Banks, we encountered two optically unique environments: 1) A self-organizing wind-driven system of alternating rows of sand and ephemeral algae; and 2) a kilometer-scale milky-white region of extremely fine-grained sediment suspended in the water column, commonly referred to as a "whiting" event. Here, we present optical measurements and SeaWiFS ocean color imagery generated for this optically shallow region. We postulate that Langmuir circulation is the mechanism that causes both the windrows or "brownings" in the coarser sediments on the eastern arm of the Bahamas and the whitings in the fine mud sediments on the western section of the Great Bahama Bank. Resuspended aragonite sediment increases the backscattering in the water resulting in greater reflectance across the visible spectrum. This relationship may be exploited to quantify resuspended sediment and potentially rates of calcium carbonate precipitation from ocean color imagery both temporally and spatially across this region of the Banks.

INTRODUCTION

The carbonate sediment shelf of the Bahamas Banks is a large, approximately 125,000 km^2, optically shallow environment that is observable from space (Fig. 1). The average depth of the Banks is approximately 4 m and the seafloor habitats include fine carbonate mud, coarse grapestone sediment, seagrass, soft and hard corals, and ephemeral benthic algae. In addition, two very unique optical features can be found in these clear shallow waters. Turbid white suspended aragonite needles or "whitings" are one striking feature of Bahamian waters that have been debated in the literature. Whitings typically occur to the west of Andros Island along the Great Bahama Bank where the bottom sediment consists of very fine-grained mud or pellet mud facies. Some have viewed whitings as spontaneous precipitates of aragonite [*Cloud*, 1962], but it has not been possible to demonstrate this process by any direct or quantitative means [*Morse et al.*, 2003]. Broecker et al. (2000) present what they call "iron-clad" radiocarbon and chemical evidence that whitings are dominated by resuspended sediment and not spontaneous precipitation [*Broecker et al.*, 2000]. However, no reasonable mechanism for sediment resuspension has been put forth [*Shinn et al.*, 1989]. The most speculative mechanism invokes the black-tipped sharks purposefully stirring up sediments in order to create a trap for fish [*Broecker et al.*, 2000]. The scale of whiting events, often several kilometers in size, may not be consistent with resuspension from movement of an individual organism.

Observations of a seemingly unrelated optical feature west of the Exuma Islands have led us to propose a new mechanism for whiting formation. In this region on the eastern arm of the Bahamas Banks, bottom sediments are much coarser and the benthic life consists of periodic blooms of ephemeral benthic algae. We observed a self-organizing wind-driven system of alternating rows of sand and brown algae. Windrows have long been associated with a type of wind-driven circulation of the upper water. Langmuir (1938) developed his theory of upper-water convection cells from observations of straight rows of algae parallel to the direction of the wind [*Langmuir*, 1938]. However, the convergence of algae in optically shallow water is not at the sea surface, as traditionally observed with Langmuir circulation, but at the bottom interface. Here, we present optical measurements of these windrows of sand and ephemeral brown algae and dub these events "brownings." We postulate that Langmuir circulation is the mechanism that causes the brownings on the western bank and the whitings on the eastern bank.

METHODS

Remote sensing reflectance

Two different methods were employed to estimate remote sensing reflectance (R_{rs}), the ratio of water-leaving radiance normalized to the plane irradiance incident on the sea surface. Measurements were made with a hyperspectral tethered spectral radiometer buoy (HTSRB, Satlantic). The radiative transfer model, Hydrolight, was used with coincident ac-9 measurements to propagate the L_u measurements above the sea surface. Above-surface radiance measurements were also taken with the Field Spec Pro™ VNIR-NIR1 portable spectrometer system from Analytical Spectral Devices. A sequence of measurements were made with a 8^o foreoptic focused at a 40-45 degree angle sequentially on a gray plaque (L_g), sea surface(L_t), and diffuse sky (L_{sky}). The L_g measurement was conducted on a plaque held parallel to the sea surface and was used to estimate spectral $E_d(\lambda)$, assuming that the gray plaque is a lambertian diffuser.

$$E_d(\lambda) = \frac{\pi L_g(\lambda)}{R_g(\lambda)}$$

The reflectivity, $R_g(\lambda)$, of the gray plaque (Kodak gray card) was not spectrally flat and was measured in the lab using the ASD and an integrating sphere. The L_u and L_{sky} measurements were used to derive an estimate of spectral L_w:

$$L_w(\lambda) = L_t(\lambda) - \left[L_{sky}(\lambda)\rho \right]$$

The reflectance, ρ, represents the proportion of incident light, which is reflected by a flat water surface at the angle of observation, as determined by Fresnel's Equation . The Fresnel reflectance for a $40\text{-}45^o$ angle of observation is 0.028 [*Kirk*, 1994] and applicable for wind speeds less than 5 m s^{-1} [*Mobley*, 1999]. Residual reflected sky radiance was then removed assuming that the reflectance at 750 nm was zero and subtracting *Rrs(750)* from *Rrs(λ)* [*Mobley*, 1999].

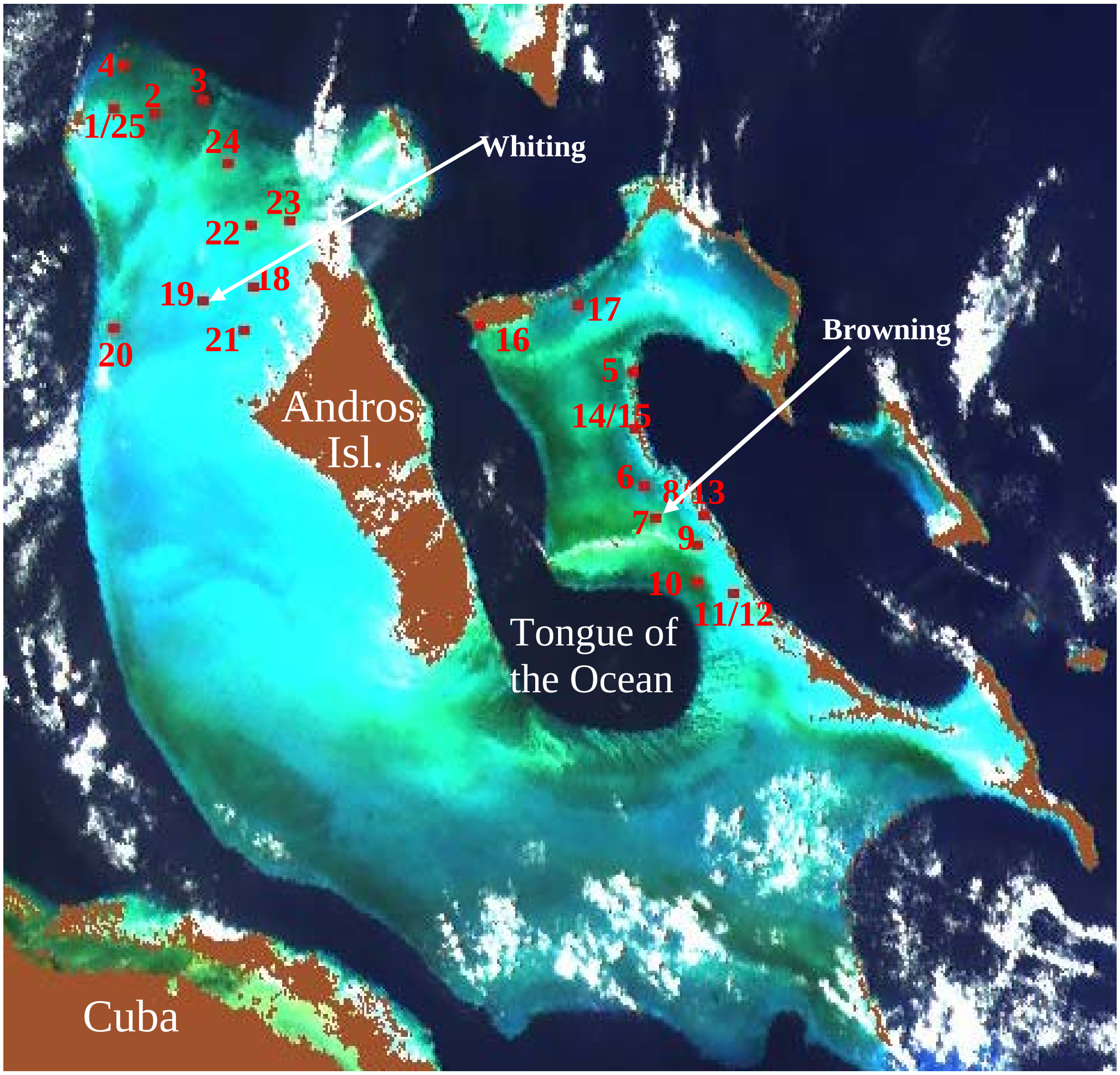

Figure 1. *True-color SeaWiFS image of the Bahamas Banks from 6 March 2004. Locations of our sampling station are shown in red. The "whiting" occurred at Station #19 west of Andros Island and the "browning" occurred at Station #7 west of the Exuma Islands.*

SeaWiFS Image processing—A high resolution (1 km) SeaWiFS Level 1A Local Area Coverage (LAC) image from 6 March 2004 provided a relatively cloud-free view of the Bahamas Banks. Atmospheric correction routines for SeaWiFS were not designed for optically shallow water. We applied an iterative scheme to first process the image using the SeaWiFS multiple-scattering atmospheric correction algorithm [*Gordon*, 1997]. The atmospheric correction scheme from neighboring deep water was identified and the entire image was then reprocessed with SeaDAS using a fixed aerosol optical depth [τ_a(865) = 0.10], and fixed aerosol model #8. A linear regression of the SeaWiFS-derived and *in situ* R_{rs} for each of the six channels was used to fine tune the atmospheric correction. The image was then georeferenced and warped based on a complete geometry model of the earth and satellite orbit using ENVI (Research Systems, Inc.).

RESULTS

Multi-spectral R_{rs} determined with the SeaWiFS sensor were in excellent agreement with hyperspectral R_{rs} measured over a variety of stations across the Bahamas (Fig. 2). SeaWiFS-derived R_{rs} were within a few percent of spectra measured at these locations. This is remarkable correspondence given the difficulties in atmospheric correction of satellite data over optically shallow water and the differences in spatial-averaging between SeaWiFS and ground-truth measurements.

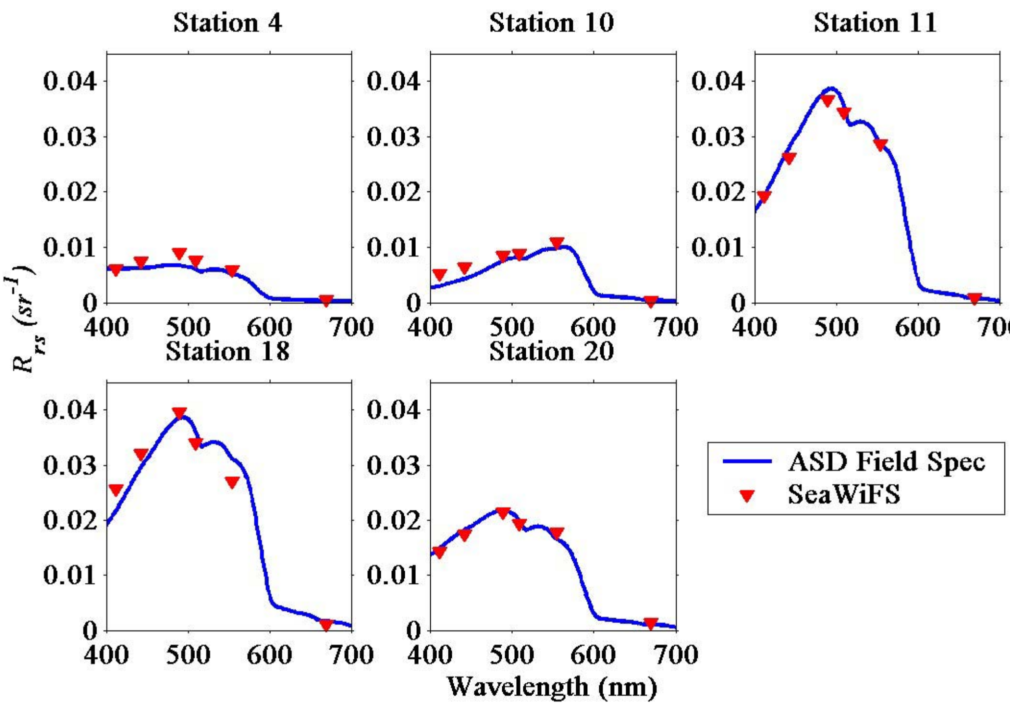

Figure 2. *Remote sensing reflectance, R_{rs}, for a variety of stations measured with the ASD FieldSpec. The red points represent the multi-spectral SeaWiFS R_{rs} for the 1km pixel nearest to each station. The in situ data was collected from 14-28 March 2004 and the imagery is from 6 March 2004.*

Low phytoplankton biomass (~0.1 mg Chl m^{-3}) results in excellent water clarity in the Bahamas Banks. Colored dissolved organic material (CDOM) is generally the dominant absorbing constituent [*Boss and Zaneveld*, 2003]. Comparisons of inherent optical properties measured with an *ac-9* reveal similar spectral shapes in the absorption and attenuation coefficients for the browning station (#19) and the whiting station (#7) (Fig. 3). The IOPs for the browning station show CDOM-dominated absorption spectra that are typical of water sampled at the other stations throughout the Bahamas Banks. In the whiting station, however, the attenuation coefficient, c, is approximately 8-fold higher than the other stations. This is consistent with the highly scattering milky-white waters containing concentrated suspended sediment. The amount of resuspended matter may be directly correlated with the backscattering coefficients of the water column.

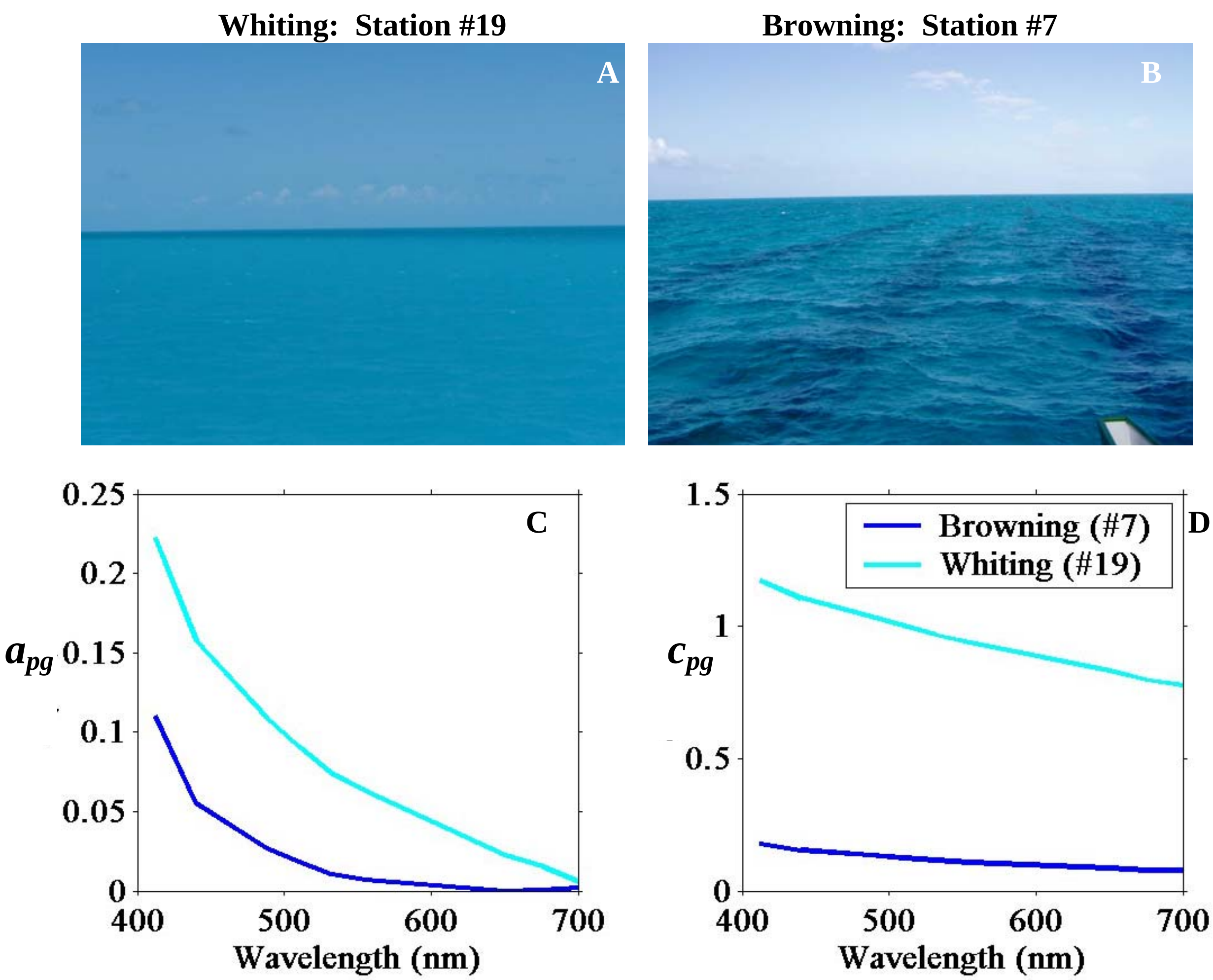

Figure 3. *A) Picture of Station #19 showing the milky-white color of the whiting and the sharp boundary with the darker water on the horizon. B) Picture of the windrows of sand and algae evident in Station #7. C) Particulate and CDOM absorption coefficient,* a_{pg}*, and D) particulate and CDOM attenuation coefficient,* c_{pg}*, of these two stations measured with an ac-9 (WET Labs)*

Station #21 had similar mud sediment and bathymetry (5.4-5.6 m) to Station #19, but was not undergoing whiting conditions. The scattering coefficient and backscattering ratio for this station were not as high as for Station #19 (Fig. 4). Station #21 had significantly higher scattering and backscattering than Station #7 and the other stations without aragonite mud sediment. This suggests that although concentrations of suspended sediment were not sufficient to produce a whiting, significant amounts of resuspended sediment were present in the water column. Similar results were evident in the magnitude and shape of Rrs (Fig. 4C). Station #21 had lower reflectance than the whiting, but significantly greater reflectance than Station #7.

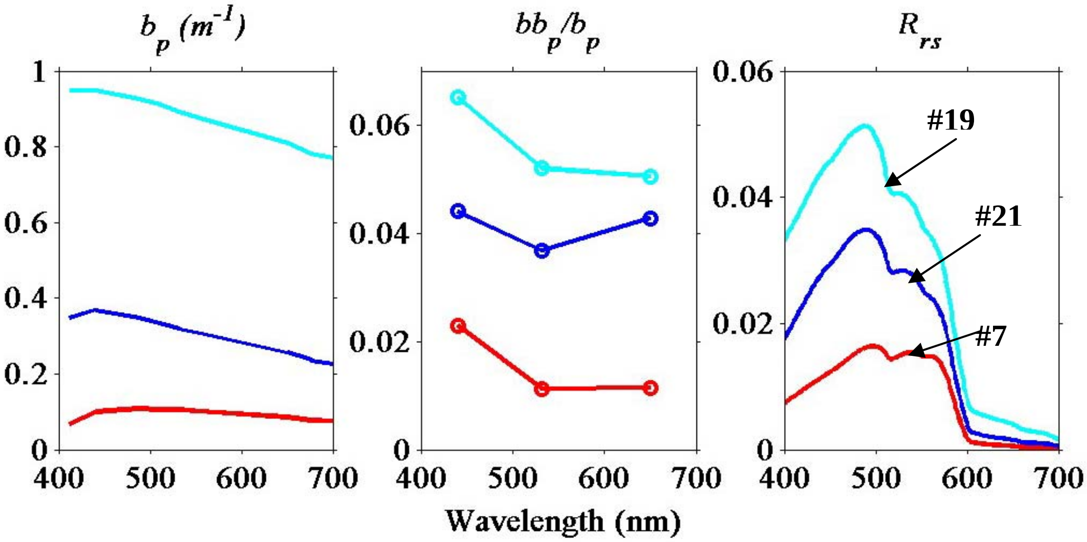

Figure 4. *A) Total particulate scattering (B) backscattering ratio (bb_p/b_p), and remote sensing reflectance (Rrs) for Station #19 (whiting), Station #21 (same benthic sediment, no whiting), and Station #7 (browning).*

CONCLUSIONS

High winds are typical of the Bahamas Banks, particularly in the spring season. Wind speeds exceeding 25 m/s were consistent for several days during our recent cruise in March 2004. Under high wind conditions, Langmuir circulation can form zones of convergence and divergence parallel to the direction of the wind [*Thorpe*, 2004]. This is the likely cause of the windrows of sand and algae evident on the eastern arm of the Bahamas Banks (Fig. 3B). The windrows were approximately 5 m in width and separated by 10 m of sand. However, unlike traditional diagrams of Langmuir circulation, negatively buoyant benthic algae converged at the bottom and were not emergent at the surface. The circulation cells acted as brooms sweeping the algae into wind rows on the seafloor. We hypothesize that winds behave similarly on the Banks west of Andros Island. High winds lead to formation of Langmuir circulation. Since the sediment is much finer on this portion of the Banks, aragonite needles become resuspended and are carried up to the sea surface. The circulation cells converge at the sea surface and the suspended sediment becomes well mixed in the water column, obscuring any evidence of wind rows. Further, the benthic features in this region of the Bahamas, include ridges of dense seagrass and patches of soft corals and sponges, would constrain the circulation patterns into discrete zones, such as those observed in whitings. This wind-driven Langmuir circulation, which has been observed on the eastern Banks, is a likely candidate for sediment resuspension and whiting formation.

Whitings do not represent massive spontaneous precipitation events, however, the dominant mode of carbonate removal on the Banks has been postulated to be via precipitation on resuspended sediments [*Morse et al.*, 2003]. Single aragonite needles may be resuspended many times over a period of decades during which they experience repeated overgrowth. Our results indicate that suspended sediment concentrations are correlated to the magnitude of the remote sensing reflectance signal. Suspended sediment increases the backscattering in the water resulting in greater reflectance across the visible spectrum. This relationship can be exploited to quantify resuspended aragonite sediment and potentially rates of calcium carbonate precipitation from ocean color imagery both temporally and spatially across this region of the Banks.

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