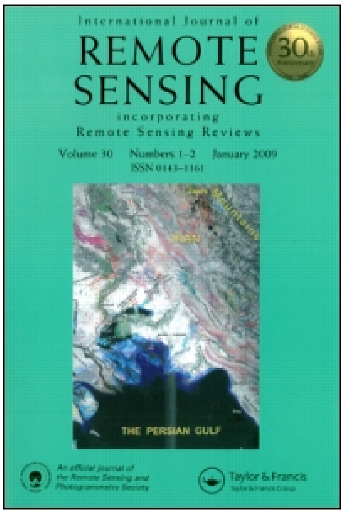

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Study of the effects of suspended marine clay on the reflectance spectra of phytoplankton

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Abstract. A controlled experiment was set up to study the reflectance spectra of phytoplankton cultures isolated from marine and fresh waters in Singapore. Typical reflectance of chlorophyll was observed in the green band (540–570 nm), whereas absorption was mainly in the blue band (400–500 nm) and red band ($\sim$650 nm). Additional reflectance peaks were observed in the near-infrared (NIR) region at 687 nm, 719 nm and 760 nm. A comparison of the spectral profiles at high and low chlorophyll concentrations indicates that there is a significantly greater increase in the overall reflectance in the (NIR) band compared to that in the visible band. Colour ratios and first derivatives at selected reflectance peaks were correlated with chlorophyll *a* content. The red–NIR ratio and first derivative at 687 nm (NIR) give the best correlations with chlorophyll *a*. When marine clays were added to the pure algal culture, a preferential increase in reflectance of light at certain wavebands was observed. When natural marine clay was added, there was a greater increase in the visible band, especially the green wavelengths, compared to that in the NIR band. In contrast, when combusted marine clay (organic content removed) was added, a relatively greater increase in reflectance in the NIR band was seen. The experimental results were able to partially explain the trends observed in spectral reflectance measurements of the coastal waters of Singapore.

1. Introduction

Concerns about coastal eutrophication have increased in recent years due to the rapid development of coastal cities worldwide. Effective management of marine resources and effective management of activities within the coastal zone is dependent, to a large extent, upon the ability to identify, measure and analyse a large number of parameters that interact together in the highly dynamic coastal environment. Satellites with ocean colour sensors provide such a tool for monitoring seawater as they have the advantage of providing synoptic views of algal distributions, thus allowing an assessment of the overall trophic state and hence, water quality of the aquatic system (Richardson 1996, Thiemann and Kaufmann 2000).

Remote sensing in the coastal zone has generally been far less successful than in

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other areas, such as open oceans or terrestrial environments (Cracknell 1999). This is mainly due to the complex interactions of the four optically sensitive substances in coastal seas, i.e. water, photosynthetic pigments in phytoplankton, yellow substances (dissolved organic matter comprising of mainly fulvic and humic acids) and suspended sediments. Each parameter has its own reflectance and absorption trends and as a result, this complicates the derivation of algorithms to estimate the level of algal biomass using remotely sensed or spectral reflectance data. While the approach has been successfully used to estimate chlorophyll *a* concentrations in a number of inland water bodies (Gitelson 1993, Gitelson *et al.* 1993, Kirk 1994, Arenz *et al.* 1996, Han and Rundquist 1997, Thiemann and Kaufmann 2000), applications to coastal water bodies, especially in the tropics, are few.

In general, the important wavelengths for the assessment of chlorophyll are in the blue (440 nm) and red (665 nm) wavebands where maximum absorption occurs, and the green wavelengths between 520 and 560 nm where reflectance is high (Zscheile and Comar 1941, Dekker *et al.* 1991, Gitelson 1992). In addition, phytoplankton also emit about 1% of the absorbed light as fluorescence with a peak at around 685 nm (Kirk 1994, Morel and Smith 1977). The general tendency is that as phytoplankton concentration increases, the reflectance decreases in the blue band (400–515 nm) and increases in the green (515–600 nm) (Clarke and Ewing 1970).

In the tropical waters of South East Asia, the large throughput of fine sediments and dissolved organic matter from storm and urban runoff can lead to difficulties in extracting that part of the spectral signal attributable to algal chlorophyll. Many studies have been conducted to explore the effects of sediments on reflectance from algal-laden water for freshwater systems, including the use of suitable wavelength ratios (Dekker *et al.* 1991, Mittenzwey *et al.* 1992, Han *et al.* 1994, Han and Rundquist 1997), differences in wavelength (Quibell 1991, Han *et al.* 1994) and spectral curvature (or derivatives) (Goodin *et al.* 1993). However, whether the results of studies conducted in temperate inland waters are applicable to tropical coastal systems is questionable. In general, the application of algorithms developed from geographically diverse regions should be tested and 'ground-truthed' with data from specific sites (Arenz *et al.* 1996).

In this study, a controlled experiment was conducted to measure the reflectance spectra of indigenous phytoplankton (isolated from both freshwater and marine waters in Singapore) and how they change with other optically sensitive environmental factors. Specifically, the objectives of this study were to (1) investigate the changes in the spectral profiles of algal cultures as total chlorophyll levels increased, (2) investigate the effects of marine clays (with and without organic content) on the spectral profiles of algal cultures, and (3) compare field data collected in eutrophic coastal waters of Singapore with the results of the controlled experiment.

2. Methods

Two different types of algae isolated from the waters of Singapore were used in this study: (1) *Oocystis*, a freshwater strain, and (2) *Nanochloris*, a marine strain. The algae were first cultured in 5 litre flasks and then transferred to either a cubic fibreglass tank, 1.2 m × 1.2 m × 1 m (figure 1) (in the case of *Oocystis*), or a barrel of radius 0.4 m and height 0.8 m (in the case of *Nanochloris*). The inner walls of the containers were painted black to minimize 'bottom' effects and reflectance of light off the sides of the walls. Spectral readings of surface irradiance were taken using a portable spectroradiometer, GER 1500 (Geophysical and Environmental Research

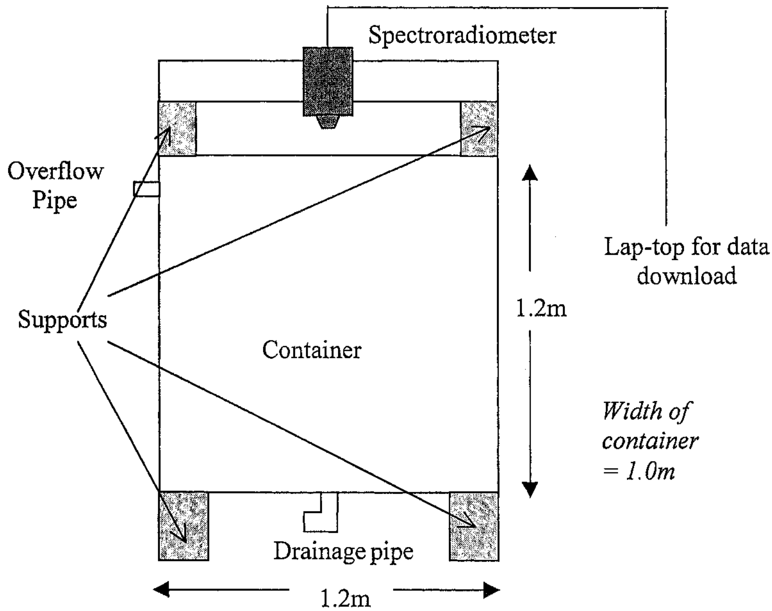


Figure 1. Experimental set-up for the controlled experiment (freshwater algae).

Corp.), which was mounted on a steel bar in such a way (perpendicular to the horizontal bar) to achieve nadir view angle (figure 1). The spectroradiometer covers 512 spectral bands, ranging from ultraviolet (UV) to near-infrared (NIR) wavelengths, i.e. 350–1050 nm. The effects of atmospheric dispersion and absorption of light were considered negligible as the distance of the spectroradiometer from the surface water was fixed at 0.5 m. Incident irradiance from the sun was measured by taking readings off a Teflon diffusing screen (Labsphere Spectralon Reflective target), which was specially designed and calibrated to reflect natural white light with minimum absorption. Water samples were collected immediately after spectral readings were taken to measure the chlorophyll *a* content. Different concentrations of chlorophyll were achieved by dilution with artificial seawater.

Chlorophyll was measured according to the method of Strickland and Parsons (1968). In the laboratory, extraction and analysis of chlorophyll were carried out under subdued light to avoid degradation of the pigments. Phytoplankton were collected by filtering 250 ml of sample onto 'Gelman Acrodist' membrane filter papers (0.45 μm). Acetone (90%) was used to extract chlorophyll *a* and the solution was sonicated for 3 min to break up phytoplankton cells. The extract was kept in the dark and stabilized in a cold room at 4° C for 24 h. The extract was centrifuged at 9000 rpm for 5 min and analysed with a spectrophotometer (Shimadzu UV-160A) (spectral bandwidth and accuracy of ± 0.5 nm).

The optical density (OD) of the chlorophyll extract was measured at four wavelengths: 750, 664, 647 and 630 nm (APHA 1995). The optical density at 750 nm (correction factor representing loss of light by scattering) was deducted from OD_{664}, OD_{647} and OD_{630}, respectively (Bowers 1996). The concentration of chlorophyll *a* was calculated by the following equation:

$$\text{Chlorophyll } a = \frac{11.85(\mathrm{OD}_{664}) - 1.54(\mathrm{OD}_{647}) - 0.08(\mathrm{OD}_{630})\} \times \text{Extract Vol.}}{\text{Sample Vol.}} \quad (1)$$

To study the effect of suspended sediment on the spectral profiles of phytoplankton, marine clay (which is dominant in this region) was added to the freshwater algae culture. Marine clay was collected from the seabed off the southern tip of Singapore (figure 2) and separated into two batches. For the first batch (which represents natural clay, containing organic matter), water was added to form a slurry, which was then wet sieved using a 20 μm nylon mesh. For the second batch, the clay was subjected to combustion in a furnace at 550°C for 48 h until all the clay solidified, giving an orange–brown appearance. (The combustion process removes any organic matter in the clays, leaving behind an inorganic clay.) The solidified clay was then pounded and blended into powder form using an electronic blender. Water was then added and mixed with the powdered inorganic clay, before wet-sieving as described earlier. Different amounts of each clay were added to the algae-laden containers to achieve different levels of suspended solids. Water samples were collected directly below the spectroradiometer after clay was mixed in the tank. These samples were filtered through 0.7 μm Whatman GF/F filter papers, which were subsequently dried at 105°C in a Memmert ULM600 oven for 2 h and left in a desiccator overnight. This process was repeated until a constant weight reading was achieved.

The experiments were conducted between 1300 and 1400 h in the afternoon. Since Singapore has significant cloud cover, the effects of differences in intensity in light were reduced by taking the percentage reflectance defined as:

$$R(\%) = \frac{T \times 100}{L} \tag{2}$$

where T is the wavelength-specific target radiance and L is the corresponding radiance measured off the labsphere spectralon reflective target.

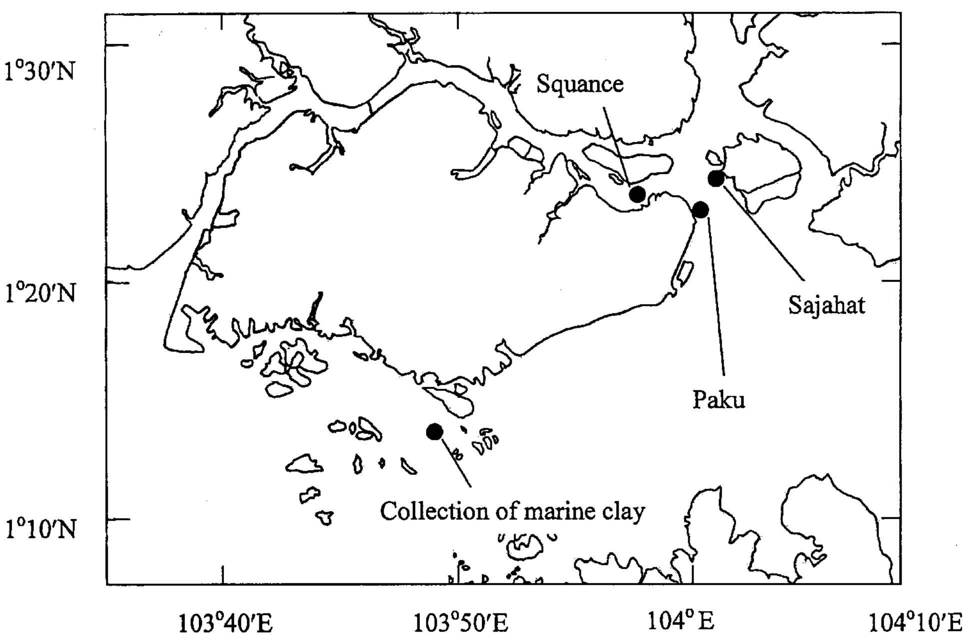


Figure 2. Sampling locations at the East Johor Strait (Paku, Sajahat and Squance); collection of marine clay off the southern coast of Singapore.

In addition to the controlled laboratory experiments, field sampling of coastal waters was conducted on a bi-weekly basis from 1997 to 1998 at three locations in the East Johor Strait (i.e. Paku (1° 23.537′ N, 104° 00.258′ E), Sajahat (1° 24.048′ N, 104° 01.036′ E) and Squance (1° 23.703′ N, 103° 57.537′ E) (figure 2). These sampling stations are situated in mesotrophic to eutrophic waters where the chlorophyll can reach levels as high as 78 μg/l (average ~22 μg/l). *In situ* measurements of surface irradiance were taken using the same spectroradiometer and water samples were collected for analysis of chlorophyll and suspended sediment.

3. Results

3.1. *Effects of a change in chlorophyll* a *on the spectral profiles of indigenous algae*

For the laboratory experiments, the chlorophyll content in the containers generally ranged from about 20 to 310 μg/l. In the case of the freshwater phytoplankton, *Oocystis*, the spectral response at different chlorophyll levels generally showed high absorption troughs in the blue (400–500 nm) and red bands (~650 nm) (figure 3(*a*)). High reflectance was recorded in the green (~540–570 nm) and NIR bands at 687 nm, the latter corresponding to the natural fluorescence of chlorophyll *a*. A comparison of high chlorophyll (180 μg/l) and lower chlorophyll (21 μg/l) conditions indicated that in the visible spectrum, the reflectance peak and absorption troughs remained relatively unchanged in the green, blue and red bands, respectively (figure 3(*b*)). However, there was a significantly greater increase in reflectance in the NIR band, compared to that of the green band for the higher chlorophyll *a* condition. For lower chlorophyll levels (21 μg/l), the natural fluorescence at 687 nm was lower than the green peak. In contrast, for the case of higher chlorophyll, the natural fluorescence far exceeded the green reflectance peak. Furthermore, two reflectance peaks (719 and 760 nm), which were not very significant when the chlorophyll concentration was low, became very distinct with higher concentration of chlorophyll.

In the case of the marine algal culture, *Nanochloris*, a high reflectance peak was registered in the green band at 550 nm and an absorption trough at 504 nm (figure 4). An absorption trough was also observed at the end of the red band at 673 nm. A comparison of fresh water and marine phytoplankton showed that for the case of the marine culture, there was a shift of the peaks and troughs in the visible spectrum towards the red end (i.e. blue trough, 8 nm; green peak, 11 nm; red trough, 19 nm) (figure 5). In the NIR band, natural fluorescence of chlorophyll *a* at 687 nm was not observed. Instead, a prominent reflectance peak was observed at 710 nm for low concentration, which shifted to the right by 5 nm when the concentration of chlorophyll increased to 311 μg/l (figure 4(*b*)). In contrast, the spectral response at the lower chlorophyll level remained relatively flat beyond the peak at 710 nm, corresponding to high absorption by water in the NIR band. This shows that when an algal bloom occurs, the upwelling irradiance generated by the phytoplankton has the ability to quench the absorption trends of water in the NIR band.

With the identification of the signature absorption and reflectance trends, simple colour ratios were chosen for correlation with chlorophyll *a* concentration. The NIR–red (687/656) ratio gave the best correlation, with R^2 greater than 0.88 (figure 6(*a*)). Since two other peaks were observed in the NIR region at 719 and 760 nm, the ratios, 719/656 and 760/656, were also tested for correlations with chlorophyll *a*. The colour ratio, 719/656, gave an R^2 of 0.81 (figure 6(*b*)) while 760/656 produced an R^2 of 0.70 (figure 6(*c*)). The blue–green ratio, on the other hand, showed poorer correlation with chlorophyll content ($R^2 = 0.50$) (figure 6(*d*)). In addition, the

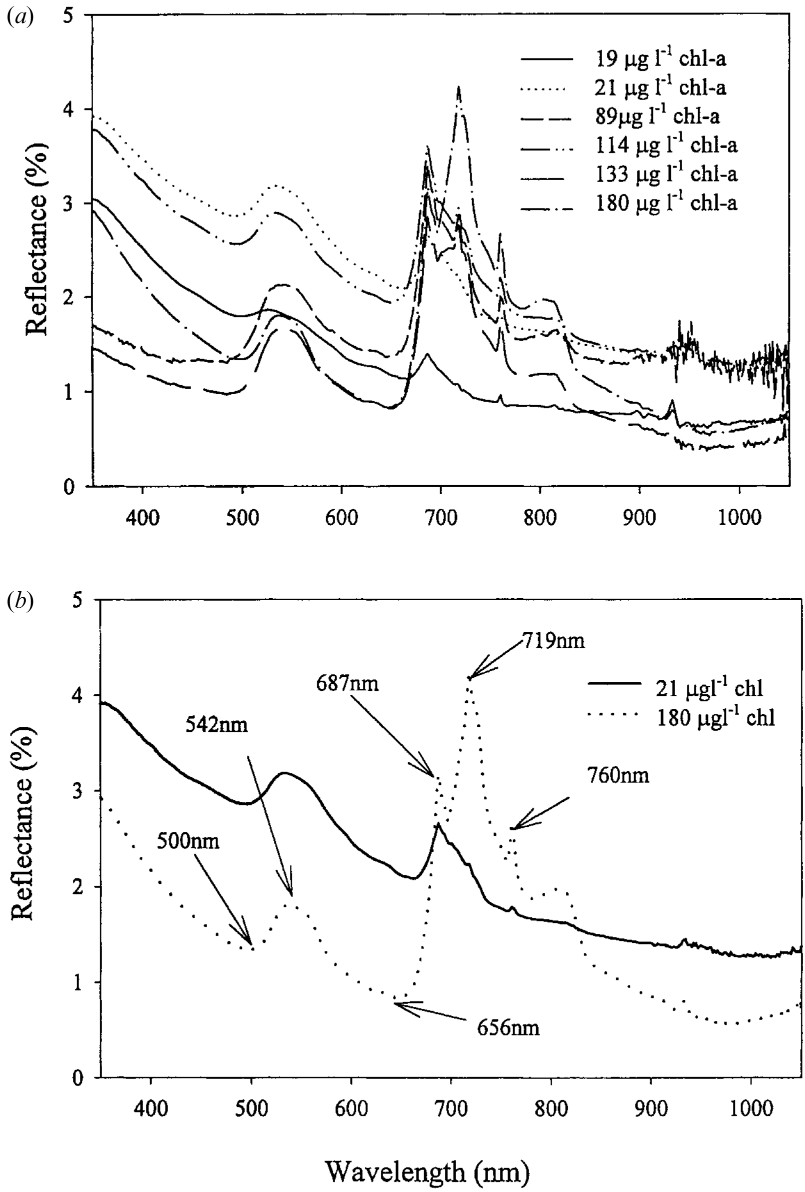
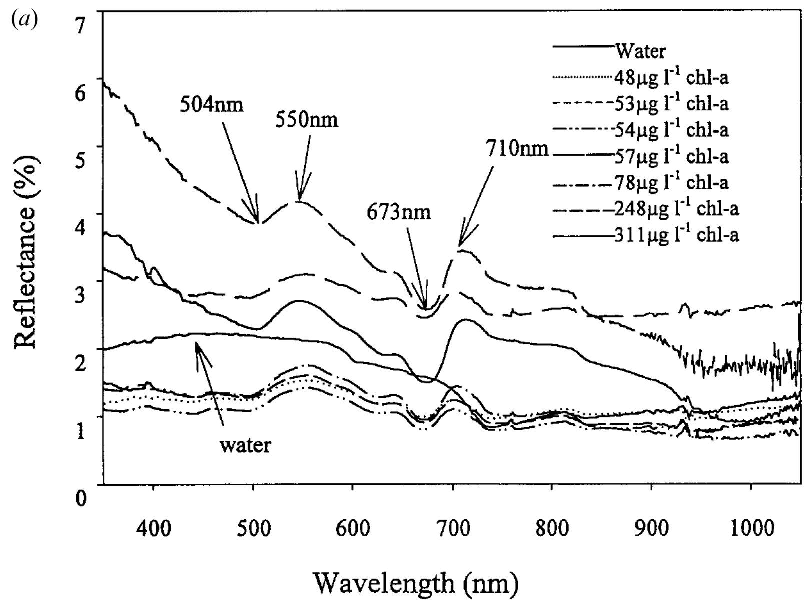


Figure 3. Spectral profiles of fresh water phytoplankton (*Oocystis*) for (*a*) varying concentrations of chlorophyll *a* and (*b*) selected chlorophyll levels of 180 μg/l and 21 μg/l.

gradients (i.e. the first derivative) near the peaks in the blue, green, red and NIR region were linearly regressed with chlorophyll content. It was found that the best correlation was achieved in the NIR band at 719 nm ($R^2=0.92$; figure 7(*a*)) and 687 nm ($R^2=0.89$; figure 7(*b*)), whereas the reflectance peak in the green band at 542 nm yielded a relatively weaker correlation ($R^2=0.73$) (figure 7(*c*)).

3.2. *Effects of suspended marine clays on the spectral profile of phytoplankton*

In order to study the effects of fine sediments on the spectral profile of the algal culture, different amounts of marine clay were added to the experimental tank



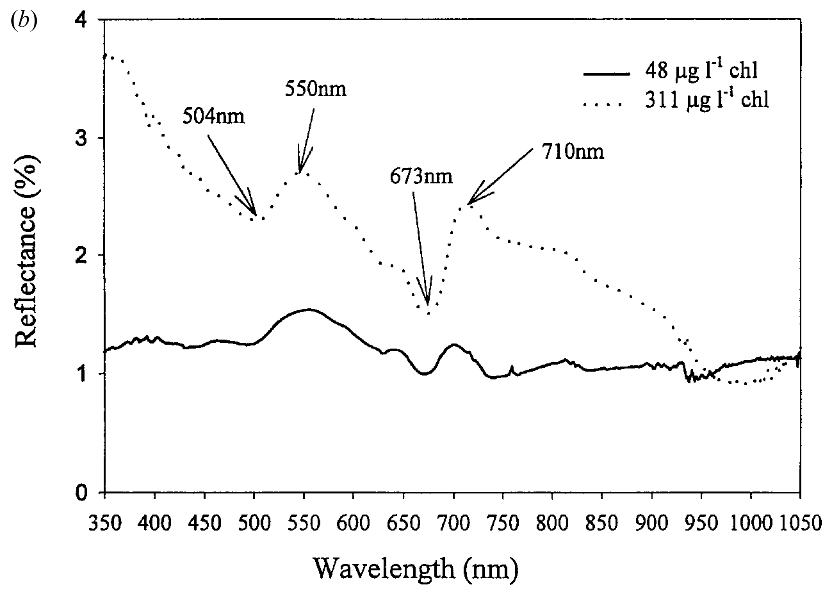


Figure 4. Spectral profiles of marine phytoplankton (*Nanochloris*) for (*a*) varying concentrations of chlorophyll *a* and (*b*) selected chlorophyll levels of 311 μg/l and 48 μg/l.

containing fresh water algae (45 μg/l Chl *a*). In general, as natural clay (i.e. containing organic matter) was added, there was an increase in the overall reflectance of the spectral profile (figure 8), but the basic shape of the spectrum still resembled that of the pure algal culture. This further confirms that the major optical characteristic of fine sediments is backscattering of light while the characteristic reflectance peaks and absorption troughs of chlorophyll *a* still remain. In the blue band, a relatively

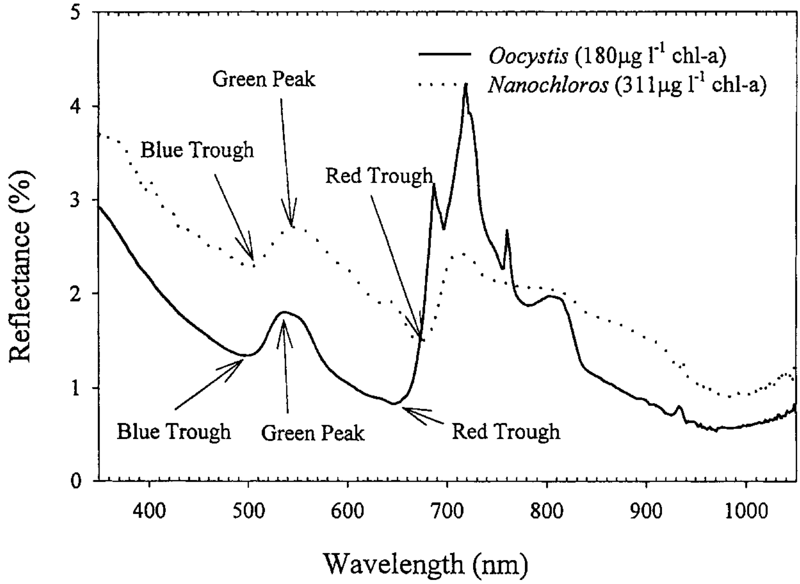


Figure 5. Comparison of reflectance spectra of freshwater and marine algal cultures.

flat response of absorption was observed, while in the green band, the reflectance peak at 558 nm became more distinct. In the red band, the absorption trough at 656 nm deepened as the green reflectance peak rose with increasing suspended clay concentration. However, the most obvious change was the greater increase in reflectance in the visible band compared to that of the NIR band. From this experiment, natural marine clay seems to have a preferential effect on different regions of the spectrum of algae-laden waters.

In the case of inorganic (combusted) clay added to algae (45 μg/l Chl *a*), the spectral profile shows greater absorption (and hence, lower reflectance) in the green band relative to the NIR band (figure 9). As with natural clay, the inorganic clay generally did not alter the locations of the peaks and troughs in the algal spectrum. However, a relatively smaller increase in reflectance was observed in the green band when inorganic sediment was added, compared to natural clay.

3.3. *Comparison of controlled experimental results with field data*

The typical spectral profile of the coastal waters of Singapore resembles that of Case 2 waters, where phytoplankton is not the dominant parameter contributing to surface irradiance (figure 10). In this particular profile, the chlorophyll *a* content was 4 μg/l and total suspended solids concentration was 45 mg/l (10% organic, 90% inorganic). The most distinct feature of the spectrum is the green peak at 574 nm, in spite of the low measured chlorophyll concentration of 4 μg/l. From the experimental results where organic sediment was added to algae, a greater increase in reflectance in the visible band was observed compared to that in the NIR band—the most distinctive increase was found in the green reflectance peak, which became higher and sharper as suspended sediment concentration increased (figure 8). This shows that the magnitude of the green reflectance peak in the field spectra is not only due to minimum absorption by chlorophyll *a*, but is also 'amplified' by the preferential backscattering of light by marine clay. In the red band, a small absorption trough

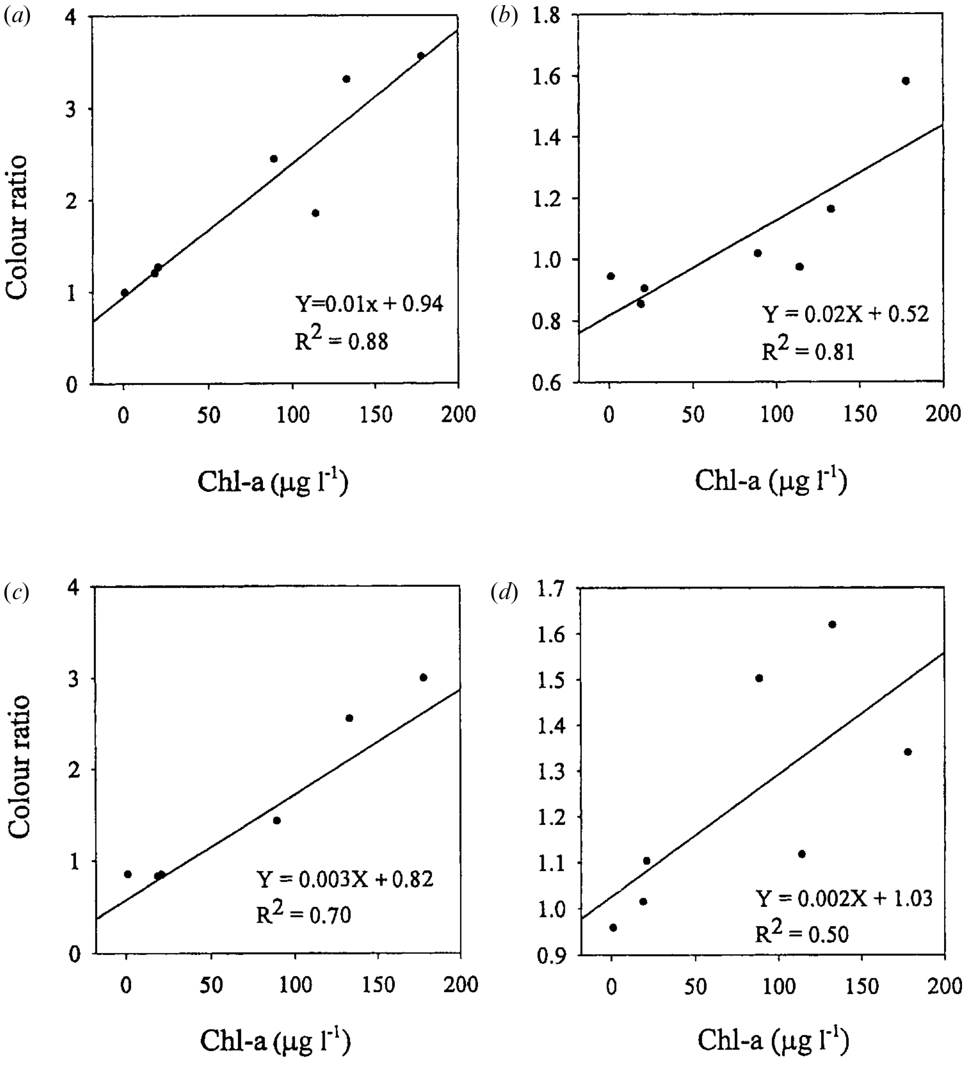


Figure 6. Correlation between chlorophyll concentration and the colour ratios (*a*) 687/656, (*b*) 719/656, (*c*) 760/656 and (*d*) 542/500.

was observed at about 670 nm, corresponding to absorption by chlorophyll *a*. A shoulder between 600 and 670 nm was also apparent, which may be due to absorption by phycocyanin at around 624 nm. In the NIR band, a very low peak was observed at 695 nm (figure 10). Two other barely visible peaks were observed at 719 and 765 nm. These two peaks were also observed in the spectral profile of the fresh water algae (figure 3(*b*)), although their magnitudes were much greater. Note that from the controlled experiment, the peak at 695 nm was as prominent as that of the green peak for lower concentrations of chlorophyll *a* (21 μg/l) but was higher than the green peak, when chlorophyll *a* exceeded 89 μg/l (figure 3(*a*)).

The spectral profile of surface water in the East Johor Strait during an algal bloom was different from that of non-bloom waters (figure 10). In this particular case, the chlorophyll content was about 63μg/l and total suspended concentration

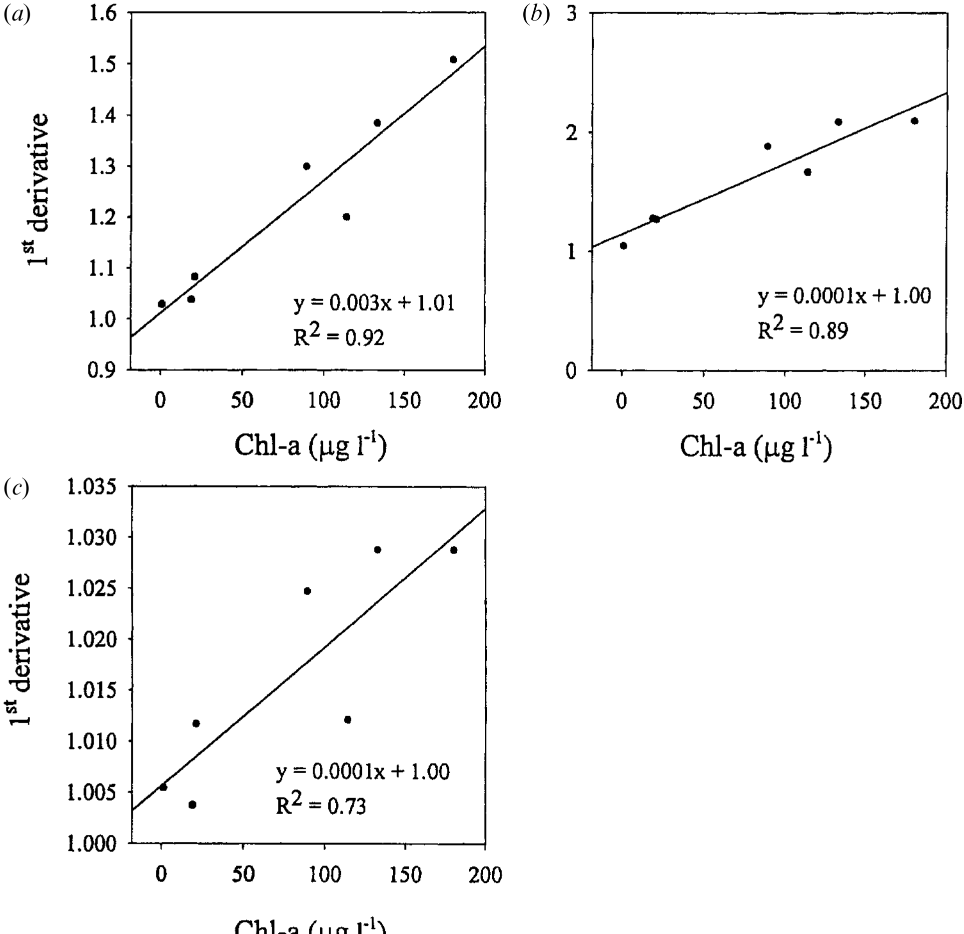


Figure 7. Correlation between chlorophyll concentration and the first derivative at (*a*) 719 nm, (*b*) 687 nm and (*c*) 542 nm.

was measured as 45.4 mg/l (71.8% inorganic, 28.2% organic). As with the previous case, the green peak and the red troughs remained at relatively the same positions. However, a comparison of the non-bloom and bloom situations showed a difference in (1) the overall % reflectance and (2) the peaks in the NIR region. The overall percent reflectance during the algal bloom lay between 3.7 and 4.5, much lower than for non-bloom conditions (figure 10). Furthermore, the green peak was not as high and distinct as that of the non-bloom situation. In the NIR band, the natural fluorescence of chlorophyll *a* at 695 nm became as distinct as the green peak.

A comparison of the spectral profile of the phytoplankton culture (chlorophyll *a* concentration of 21 μg/l) with that of the algal bloom in the Western Johor Strait showed a strong resemblance between the two (figure 11). Thus, during an algal bloom with high chlorophyll concentration, one can expect a distinctive peak in the NIR band in addition to the green peak, and the difference between the two peaks should not be very high.

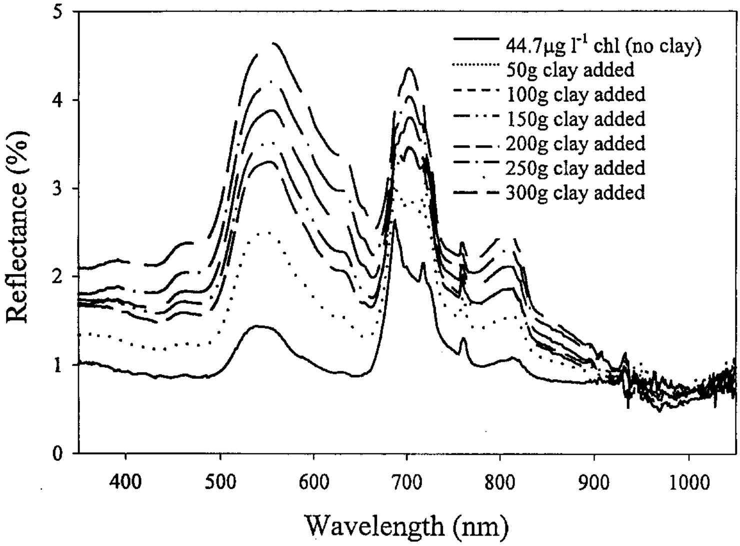


Figure 8. Spectral profiles of fresh water phytoplankton with the addition of natural marine clays.

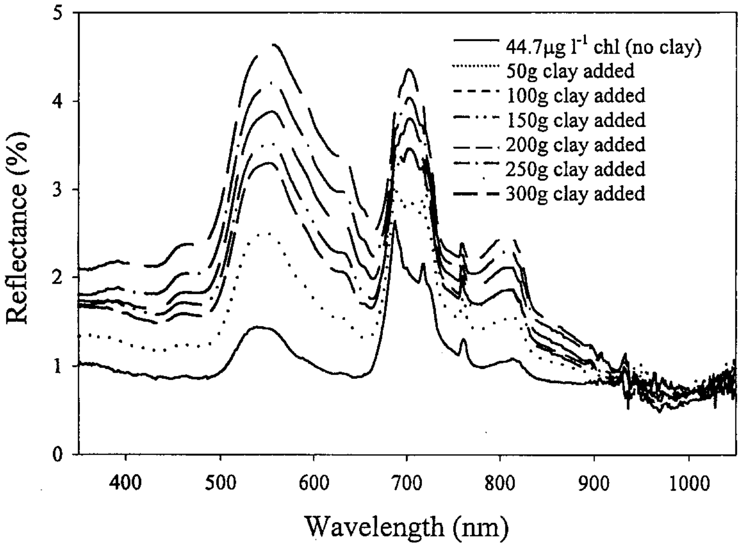


Figure 9. Spectral profiles of freshwater phytoplankton with the addition of combusted marine clay (i.e. with organic content removed).

4. Discussion

4.1. *Reflectance spectra of algal cultures*

As expected, the algal cultures show high absorption in the blue and red bands, and high reflectance in the green and NIR regions, consistent with many other studies for both field and cultured samples (Zscheile and Comar 1941, Gitelson 1993, Arenz *et al.* 1996). However, some differences were apparent between the freshwater and marine algae. In the case of the freshwater species, an increase in chlorophyll led to a substantial increase in reflectance in the NIR relative to the green peak. In

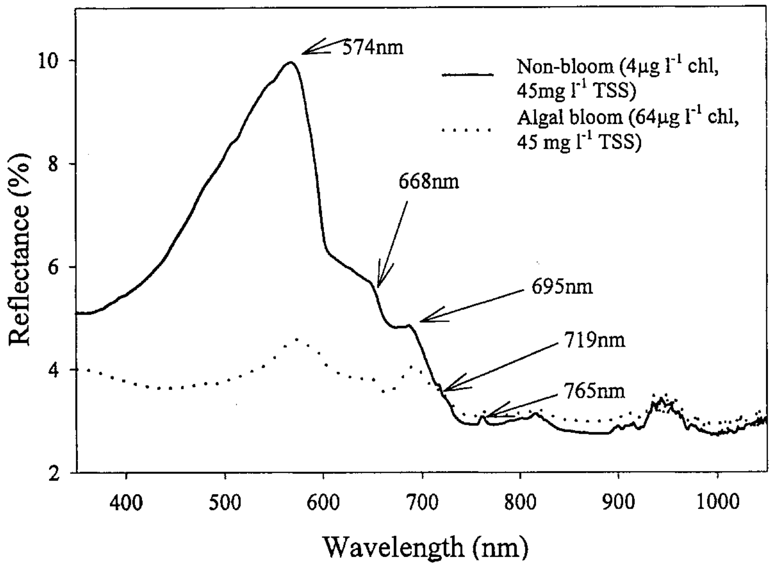


Figure 10. Comparison of spectral profiles of surface waters in the Johor Strait during bloom and non-bloom condition.

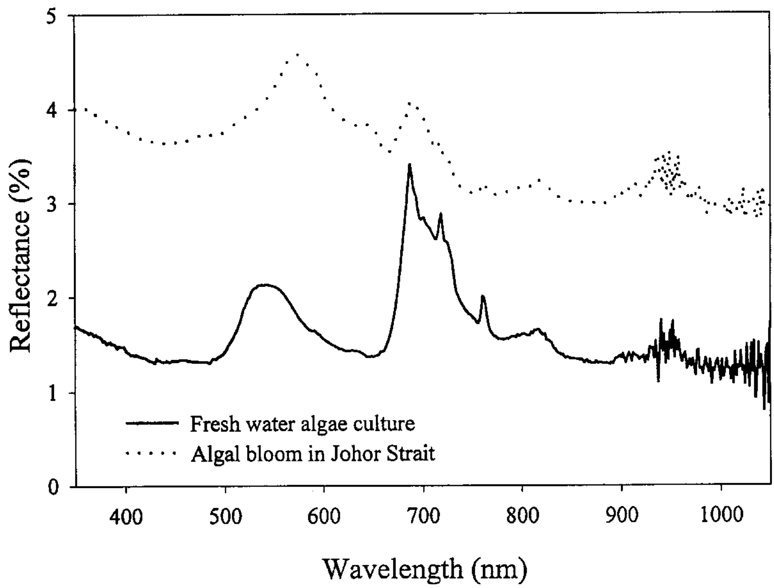


Figure 11. Comparison of reflectance spectra from an algal bloom in the Johor Strait (Chl ~ 64 μg/l) and the controlled experiment using freshwater algae (Chl ~ 89 μg/l).

particular, the chlorophyll fluorescence peak at 687 nm (Morel and Smith 1977, Kirk 1994) and localized peaks at 719 and 760 nm became more prominent. These results are similar to studies of Colorado reservoirs (Arenz *et al.* 1996), European lakes (Gitelson 1992, Thiemann and Kaufmann 2000) and wastewater oxidation ponds (Gitelson *et al.* 1997), where increases in the peak magnitude of NIR reflectance (~ 700 nm) were observed with increases in chlorophyll. The reflectance peak at about 700 nm can be attributed to decreasing chlorophyll absorption and increasing water absorption in the NIR zone (Thiemann and Kaufmann 2000). In these studies, a shift in the NIR peaks toward longer wavelengths was also observed. Gitelson (1992), in particular, found that the position of the peak near 700 nm was very closely related to chlorophyll concentration. However, in our study, this phase shift was only seen for the spectra of marine algae (*Nanochloris*) and not for the freshwater algae (*Oocystis*).

4.2. *Colour ratios*

The basic principle of colour ratios involves two wavebands which show characteristic optical trends of chlorophyll: one corresponding to high absorption and the other, low absorption. In ocean colour remote sensing, the four characteristic bands related to chlorophyll are the blue, green, red and NIR bands. In this study, the blue/green and NIR/Red ratios were tested under controlled conditions. The correlation of chlorophyll with the blue/green ratio was not as good, partly due to the greater penetrating power of blue and green light that results in interference with the base of the container. In natural samples, the use of the blue–green ratio is complicated by the combined absorption effects of dissolved organic matter, tripton and chlorophyll at blue wavelengths less than 500 nm, thus making it difficult to resolve these components (Gitelson *et al.* 1997). Some studies have also suggested the use of green–NIR ratios, but there are some conflicting results for the prediction of chlorophyll: strong correlations for the NIR–green ratios (e.g. 800/571, 700/560, 695/573) have been found for a number of inland lakes ($R^2 > 0.9$) (Gitelson and Keydan 1990, Gitelson 1992, Arenz *et al.* 1996), whereas other studies have shown a poor correlation ($R^2 < 0.19$) (Thiemann and Kaufmann 2000).

In contrast to the ratios involving blue and green wavelengths, the NIR–red ratios and first derivatives in the NIR region (i.e. at 687 and 719 nm) gave better correlations ($R^2 \sim 0.7$–0.9), consistent with other studies of inland lakes (Gitelson and Kondratyev 1991, Dekker 1993, Thiemann and Kaufmann 2000). However, the use of the NIR–red ratio also has some limitations. It has been said, for example, that the NIR–red ratio becomes less predictable for chlorophyll concentrations less than 10 μg/l, whereas it works well for much higher levels of chlorophyll (Mittenzwey *et al.* 1992). For highly turbid waters, the NIR–red ratio has been shown to be less effective at predicting chlorophyll due to the interference by sediments (Han and Rundquist 1997). Instead, the use of first derivatives in the NIR region ($\sim$690 nm) was found to be better at estimating chlorophyll when sediments were present (Goodin *et al.* 1993, Rundquist *et al.* 1996, Han and Rundquist 1997).

In our study, we tested the effects of marine clay on the reflectance spectra of algae and observed an overall increase in spectral reflectance due to scattering. While some studies have observed a uniform increase across the spectrum (Han *et al.* 1994), our results show a preferential increase in green reflectance and higher absorption in the blue waveband for the addition of natural marine clays, compared to clays with their organic content removed. Gitelson *et al.* (1997) also found increases in green reflectance for turbid wastewater and in fact, used this to estimate suspended matter concentrations. Higher absorption in the blue, on the other hand, can be attributed to the organic content of natural clays, similar to the effect of DOC (Davis 1980, Davies-Colley 1983, Arenz *et al.* 1996). In addition, strong reflectance in the NIR was also observed, particularly around 700, 750 and 810 nm, similar to other findings when tripton was present in natural samples (Chen *et al.* 1991, Arenz *et al.* 1996).

4.3. *Reflectance spectra of coastal waters in Singapore*

The chlorophyll *a* concentrations in the coastal waters of the East Johor Strait range from about 1 to 80 μg/l, with an average value of 22 μg/l. This large variability in chlorophyll is due to the variable nature of land-based inputs into a semi-enclosed water body, subject to tidal flushing (Gin *et al.* 2000). As a result, the reflectance spectra captured in this study cover conditions of both low and high chlorophyll in the presence of sediments. (Note that DOC was not measured in this study.) To some extent, the results of the controlled experiment can explain the trends observed in the field spectra. The difference between bloom and non-bloom conditions lies primarily in the relative importance of the green and NIR bands: as chlorophyll concentration increases, the difference in magnitudes of the two peaks becomes smaller and absorption is significant at visible wavelengths leading to a decrease in overall reflectance. In addition, the presence of suspended clay particles also serves to increase scattering and hence, reflectance.

Another feature observed in the field spectra is the shoulder at about 625 nm, which is more apparent at lower chlorophyll concentrations. This is presumably due to absorption (at 624 nm) by the accessory pigment, phycocyanin, typically found in cyanobacteria (Gitelson *et al.* 1997, Thiemann and Kaufmann 2000). Evidence to support this are the measurements of cyanobacteria, *Synechococcus* (Gin *et al.* 1999), and size-fractionated chlorophyll (Gin *et al.* 2000) for the same water body. In general, it was shown that small cells, such as cyanobacteria, contributed a higher proportion of total chlorophyll under more oligotrophic conditions, while larger cells (diatoms) dominated during high chlorophyll or bloom conditions for these waters (Gin *et al.* 2000).

5. Conclusions

In this study, experiments were conducted to enhance the understanding of the effects of increased chlorophyll and suspended sediment levels on reflectance spectra (and ultimately, remote sensing signatures) for the tropical, coastal waters of Singapore. Overall trends in the reflectance spectra were consistent with many other studies, including typical absorption in the blue and red bands, and reflectance in the green and NIR bands. For the algal cultures, increasing chlorophyll resulted in greater NIR reflectance but decreased reflectance in the blue-green wavebands. This led to good correlations between chlorophyll and the NIR–red ratio, as well as the first derivatives at selected peaks in the NIR band. The presence of fine sediments (marine clays) influences the reflectance spectra of algae-laden waters, resulting in increased backscattering of light, especially in the green band. One of the questions we did not address was the influence of dissolved organic matter on the spectrum, which is likely to be significant in tropical coastlines with mangroves. In the case of Singapore, however, few mangroves remain as the coastline is highly developed. Hence, the influence of dissolved matter may not be as important here as for other pristine tropical coastlines. Nevertheless, an in-depth study of the effects of dissolved organic materials would be useful to provide a more complete explanation of reflectance spectra captured in this region. This is work in progress.

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