Case 2 Climatology of NZ: Final report

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Executive Summary

This project has produced two climatologies of biogeochemical properties of the New Zealand coastal zone using over six years of satellite remotely-sensed observations of ocean colour from the NASA SeaWiFS sensor. The work involved three stages:

I. Development and implementation of a Case 2 processing algorithm for the New Zealand coastal zone. The algorithm has the following parts:

- Radiometric calibration of top-of-atmosphere measurements
- Identify and screen clouds, land and low-quality data from further processing
- Perform atmospheric correction using Case 2 Bright Pixel method
- Convert ocean colour to spectral absorption and backscatter using Inherent Optical Property (IOP) algorithm
- Scale backscatter at 490 nm which is related to total suspended particulate material concentration
- Use a function of spectral absorption at two bands which is related to dissolved organic matter absorption

The relationships between inherent optical properties (absorption and backscatter), and biogeochemical properties such as coloured dissolved organic matter (CDOM) absorption, and total suspended particulate material (SPM) concentration, change with region. Ensuring that Case 2 remote sensing products are valid regionally hence requires detailed knowledge of the characteristic bio-optical properties of phytoplankton, SPM and CDOM over all regions of interest. Suitable data do not exist currently for the whole New Zealand coastal zone. As a first step, we have used a single, New Zealand-wide relationship based on measurements taken in Golden Bay, Tasman Bay, the Marlborough Sounds, and the Bay of Plenty. This means that general onshore-offshore patterns in the Case 2 products in a given area may be expected to be reasonable, but comparisons of the absolute values of the products between different coastal regions of New Zealand are unlikely to be meaningful.

II. Processing and mapping of the archived 4 km resolution data to a standard projection. The years 1997–2004 (inclusive) have been processed, and the images have been remapped.

III. Long-term log-averages of the results were produced to represent our best estimate of the climatological mean condition for both SPM and CDOM absorption. The climatological mean values have been output in a format suitable for use with the Marine Environment Classification scheme, on a Mercator Projection, at approximately 4 km spatial resolution.

Introduction

Satellite remote sensing of ocean colour can be used to map distributions of coloured water constituents over large spatial (10^3 to 10^7 m) and temporal (6 h to decadal) scales. "Case 1" waters are those waters where variations in water colour depend solely on the concentration of phytoplankton (Gordon & Morel 1983). These waters are typically oceanic, and are not influenced by river run-off or coastal resuspension of sediment. "Case 2" waters are those where the water colour depends on coloured material not of local phytoplankton origin, such as suspended sediment and/or dissolved yellow substance from land run-off.

Operationally, Case 2 waters were defined by Mueller et al. (2002) as those where absorption due to dissolved organic matter at 380 nm is greater than 0.1 m^{-1}, and/or total suspended particulate matter concentration is greater than 0.5 g m^{-3}. Methods of estimating the concentrations of coloured water constituents that have been developed for oceanic waters fail in coastal waters for two reasons. First, the normal "open-ocean" method of correcting for light scattered into the satellite sensor by the atmosphere does not allow for the reflectance of near infrared radiation by suspended inorganic sediment in the surface water. The presence of even modest quantities of inorganic suspended sediment (more than ~0.2 g m^{-3}) in the water can lead the atmospheric correction method to fail and give invalid estimates of water constituents. Second, simple band-ratio retrieval algorithms cannot discriminate between chlorophyll, sediment and dissolved organic matter. The processing described below has been developed to overcome these limitations, and allow sediment and dissolved organic matter to be mapped using ocean colour observations of the New Zealand coastal zone.

Calibration, Cloud screening, Atmospheric Correction

This study only used data from the NASA SeaWiFS ocean colour satellite sensor (Hooker et al. 1992). Top-of-atmosphere radiance measured by the SeaWiFS sensor are converted to radiance units using a complex calibration procedure that takes into account the pre-launch characterisation of the SeaWiFS instrument, and changes to the performance of the sensor since launch. This study used the SeaWiFS Data Analysis System (SeaDAS), Fu et al. (1998), to calibrate the SeaWiFS data. Changes in SeaWiFS radiometric performance are assessed by a combination of on-orbit methods (calibration lamp, viewing of the lunar disk, viewing of a solar-illuminated diffuser), and vicarious methods based on the Marine Optical Buoy (MOBY) moored near Hawaii (Clark *et al.* 1997; Eplee et al. 2001; Barnes et al. 1998, 2001; McClain et al. 1994).

The high quality of the SeaWiFS calibration achieved using a full pre-launch sensor characterisation and ongoing calibration has been critical in ensuring high quality data through the SeaWiFS mission. This result contrasts with the Coastal Zone Color Scanner (CZCS) mission (Clark 1981), where sensor design flaws combined with untracked sensor degradation through the mission eventually compromised data quality (Gordon et al. 1983).

Following calibration of the top-of-atmosphere radiometric data, clouds and land pixels are excluded from further processing using a top-of-atmosphere radiance threshold (Darzi 1992). The method used is conservative, in that data of marginal quality at the edges of clouds are excluded. Top-of-atmosphere data are then corrected for the effects of the intervening atmosphere. The standard SeaWiFS method for estimating water-leaving reflectance from top-of-atmosphere measurements is the Dark Pixel (DP) atmospheric correction method (Gordon 1997; Gordon & Wang 1994; Wang 2000). In order to estimate top-of-atmosphere radiance due to scattering by atmospheric aerosols in the visible bands, the DP method assumes negligible water leaving radiance in the near infra-red part of the spectrum (NIR, 650–900 nm). An iterative method (Siegel et al. 2000) has been added to the DP atmospheric correction method to correct for non-negligible water reflectance in the NIR arising from moderate to high phytoplankton abundances (chlorophyll concentrations greater than ~2 mg m^{-3}). The modified DP method fails in the presence of even modest quantities of suspended sediment (>0.2 g m^{-3}) because NIR water-leaving radiance in these circumstances is not negligible, and is not related to phytoplankton abundance. This limitation of the efficacy of the DP atmospheric correction method prevents SeaWiFS measuring water leaving radiance over turbid waters and curtails applications in the coastal zone, such as monitoring sediment transport and observing phytoplankton abundance where it co-occurs with sediment.

To resolve this problem, a coupled water-atmosphere model has been developed (Lavender et al. 2005; Moore et al. 1999) which estimates ocean colour from SeaWiFS top-of-atmosphere radiometric measurements where the NIR water reflectance is dependent on suspended sediment concentration The model is implemented within SeaDAS so as to use the functionality provided by this software. We incorporated the Case 2 atmospheric correction algorithm into a more recent version of SeaDAS than that reported in Lavender et al. (2005): version 4.5 rather than 4.1. Other atmospheric correction methods applicable to turbid waters have been developed (e.g. Ruddick et al. 2000), but these often rely on an assumption of spatial homogeneity of aerosol type over at least a portion of the image. The Lavender et al. (2005) algorithm used in this study does not rely on such an assumption, and instead performs a pixel-by-pixel atmospheric correction of the top-of-atmosphere data.

The atmospheric correction method has not been validated in New Zealand waters, but has been tested and found to work effectively over coastal turbid waters around Europe. Validation of the modified atmospheric correction method in New Zealand forms the basis of ongoing research and fieldwork by the authors.

Inherent Optical Property Algorithm

The Inherent Optical Property (IOP) algorithm was used to estimate spectral absorption and backscatter from atmospherically-corrected measurements of remotely sensed reflectance at visible wavelengths: 412, 443, 490, 510, 555 nm. A description of the algorithm used in this project is given by a scientific paper that has been submitted (Pinkerton et al. In Review). The algorithm is subject to ongoing development.

This algorithm was developed on large bio-optical datasets of European and north Atlantic waters, and has been tested against a large synthetic dataset considered to represent the wide range of bio-optical conditions likely in New Zealand coastal waters. Measurements of inherent and apparent optical properties were made at 19 coastal stations off the north coast of New Zealand's South Island in December 2001. The New Zealand measurements were used to characterise the range of bio-optical properties of coloured material (phytoplankton, sediment, and CDOM) likely to occur in New Zealand coastal waters. Based on these characterisations, a radiative transfer model was used to produce a large number (5000) of modelled (or "synthetic") ocean colour reflectance spectra representing a wider range of biogeochemical conditions than were measured in the study area. The synthetic data spanned a wide range of chlorophyll concentrations (0.1–10 mg m^{-3}), total suspended particulate material concentrations (0.1–50 g m^{-3}), and CDOM absorption (0.01–3 m^{-1}). The modelled reflectance spectra were validated against measured spectra at each of the bio-optical stations. The modelled spectra were then used to test the performance of the IOP algorithm in estimating the absorption (a) and backscattering (b_b) coefficients. The results shown in Figures 1 and 2 indicate that the algorithm is effective at estimating Inherent Optical Properties across two orders of magnitude.

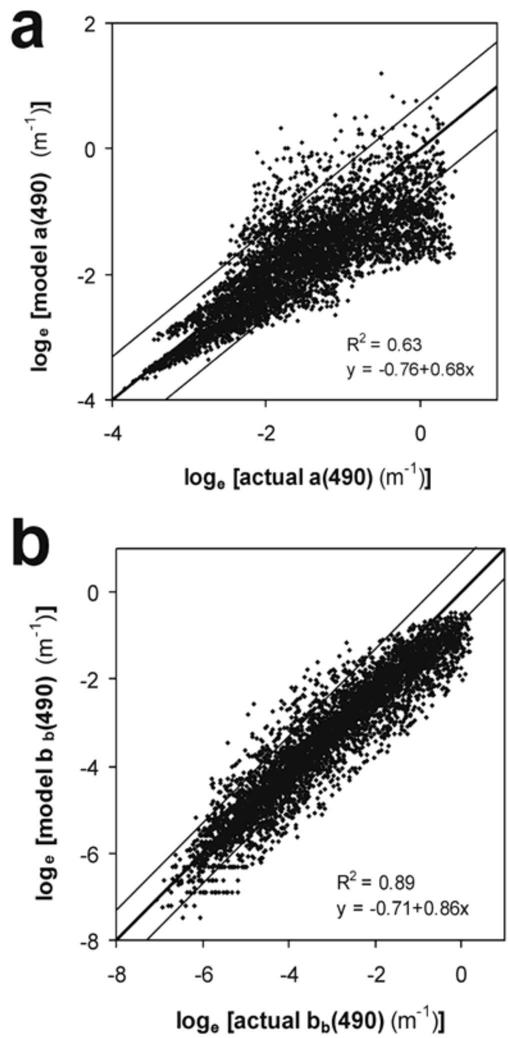

Figure 1: **Performance of the algorithm at 490 nm a: Algorithm estimates of absorption at 490 nm compared to synthetic, or target, values, on log-log scale. b: Algorithm estimates of backscatter at 490 nm compared to synthetic, target values, on log-log scale. The heavy solid lines indicate 1:1 correspondence. The lighter lines indicate errors of +100% and -50%. The equation of the least squares regression line and coefficients of determination are shown.**

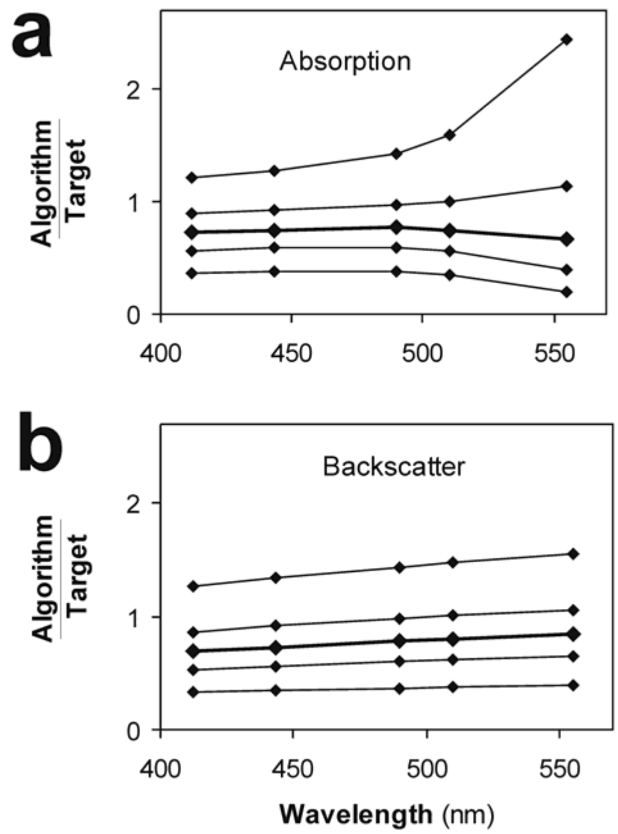

Figure 2: **Performance of the algorithm at all spectral bands. a: Absorption; b: Backscatter. The lines indicate (from bottom) the 10th, 30th, 50th (heavier), 70th and 90th percentiles of the results.**

Conversion to Biogeochemical Properties

Estimation of biogeochemical properties, such as suspended sediment and CDOM absorption, from IOPs is non-trivial. It is well known that the relationships between IOPs and biogeochemical variables are highly variable between different bio-optical provinces, depending on the nature of inorganic sediment (particle size distribution, particle shape, particle minerology etc), and the local phytoplankton species composition (e.g. Bale et al. 1994; Bricaud et al. 1995; Babin et al. 2003a, b). The use of a two-part algorithm, where we first estimate IOPs and thence estimate biogeochemical properties, means that we can "tune" the second part of processing to better reflect local bio-optical conditions using a relatively small set of coefficients.

Such regional tuning requires detailed knowledge of the characteristic bio-optical properties of phytoplankton, sediment and dissolved yellow substance over the region of interest. There is a paucity of measurements of the regional and seasonal variation of bio-optical properties of optically active material in New Zealand coastal waters. In the first instance, we used a method based on measurements in Golden Bay, Tasman Bay, the Marlborough Sounds, and the Bay of Plenty, augmented where necessary by non-New Zealand values from the scientific literature. The general scheme is as follows.

The spectral IOPs input to the second part of the algorithm are:

(1) Absorption of water constituents $a(\lambda)$ where λ =412, 443, 490, 510, 555 nm
(2) Backscattering coefficient, b_b at 490 nm

The second part of the IOP algorithm uses these IOPs to estimate the biogeochemical variables:

C_a = chlorophyll-a concentration (mg m-3)
SPM = Total suspended particulate matter concentration (g m^{-3})
$a_g(\lambda)$ = Coloured dissolved organic matter (CDOM) absorption (m^{-1})

First, SPM concentration is estimated by quadratic scaling of $b_b(490)$ as Equation 1, where B is an array of four coefficients applicable to the region described previously..

$$SPM = B_3 + EXP(B_2 b_b^{\,2} + B_1 b_b + B_0) \quad [1]$$

SPM is then constrained to lie between 0.05 and 200 g m^{-3}.

Suspended sediment in the New Zealand coastal zone was found to absorb across the visible spectrum, in a similar spectral way to CDOM (Bricaud et al. 1981). This is likely to be due to organic detrital matter coating the suspended particles. We hence correct the measured total absorption of water properties at 443 nm and 490 nm for absorption due to sediment, using Equations (2) and (3).

$$a(443)_c = a(443) - \left[A_0 SPM^2 + A_1 SPM\right] \quad [2]$$
$$a(490)_c = a(490) - \left[A_2 SPM^2 + A_3 SPM\right] \quad [3]$$

The empirical array coefficient, A, was derived from bio-optical fieldwork in the region described previously.

CDOM absorption at 440 nm [$a_g(440)$] can then be estimated as Equation 4 (Moore & Aiken 2005):

$$a_g(440) = D_0 a(443)_c + D_1 a(490)_c \quad [4]$$

As this algorithm is based solely on fieldwork in regions where the sediment is relatively labile, organic rich and fine-grained (muddy and silty), it is unlikely that the scheme here will be accurate in regions of highly refractory sediment, such as glacial run-off from the west coast of South Island. This can lead this method to give negative values of $a(443)_c$ and $a(490)_c$, and hence fail to estimate $a_g(440)$. In this case, we default to estimating $a_g(440)$ as Equation (5). The empirical array coefficient, D, was derived from bio-optical fieldwork in the region described previously.

$$a_g(440) = D_2 a(443) \qquad [5]$$

Finally, values of $a_g(440)$ outside the range 0.01–1.5 m^{-1} are set to "missing".

In open-ocean waters where the algorithm failed to provide a reasonable value for sediment concentration (SPM) and/or CDOM absorption (a_g), but there was a reasonable estimation of chlorophyll concentration by the SeaWiFS OC4v4 algorithm, we used empirical relationships to estimate SPM and CDOM from the OC4v4 result. This method used 10,000 randomly selected pairs of measurements to develop a relationship between chlorophyll-a concentration and SPM using least-squares linear regression in log-log space. A similar relationship was obtained between CDOM absorption and chlorophyll-a concentration. These relationships are only considered valid for Case 1, open-ocean regions.

Remapping, Climatological Analysis and Output

Each individual Global Area Coverage image obtained by the SeaWiFS ocean colour satellite between day 251 year (6 September) 1997 and day 358 year (24 December) 2004 in the New Zealand region was processed as described. Each of these images was remapped as a Cylindrical Projection with a mapped average resolution of approximately 4356 m. In all, 7557 individual files were considered. Data was used from 6679 of these (88%). The remaining files did not cover the study region or had no valid data.

Data were excluded due to cloud contamination, atmospheric correction failure, algorithm failure or based on satellite sensor quality control tests. On average, about 500 individual measurements were combined to produce each individual data value in the climatological dataset, but this varied with location (Figure 3). Higher data coverage occurred to the north-west of the study region, and around the Cook Strait region (up to 1000 individual measurements per output data value). Lower coverage occurred to the south of the study region (<200 measurements per output data value), largely because of greater cloud cover to the south.

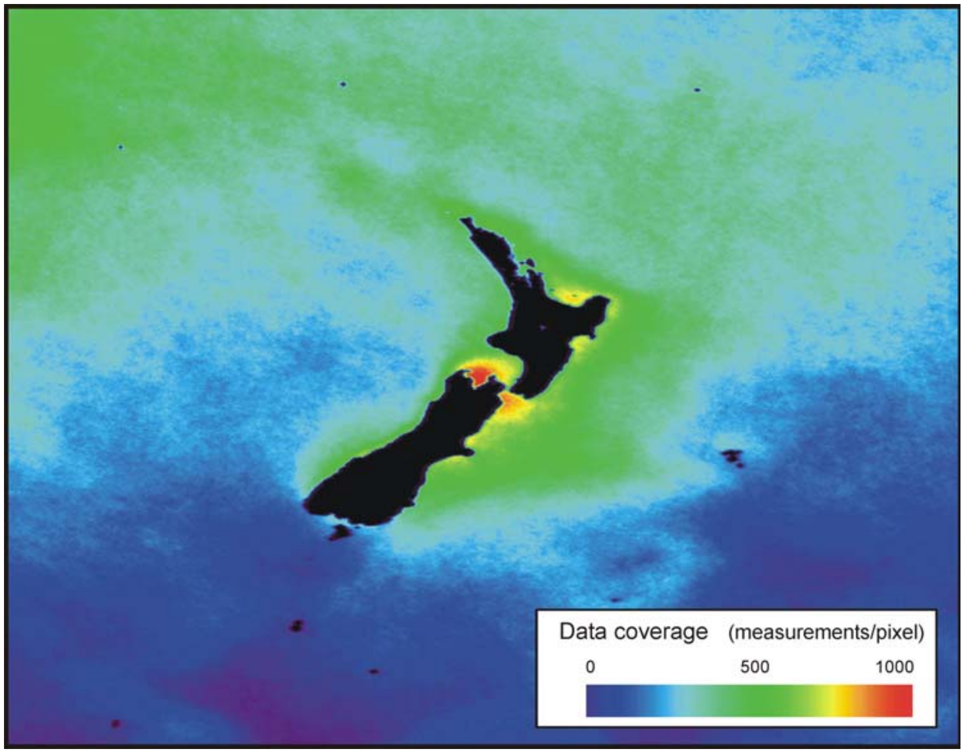

Figure 3: **Date coverage used in producing the climatological values. The colours indicate the number of individual measurements used to produce the output data value at each location (pixel).**

There was little systematic seasonal variation in SeaWiFS data availability through the study period. To illustrate this fact, we calculated the number of valid SeaWiFS GAC files used in the analysis in an arbitrary 15-day period (Figure 4). On average, considering the whole study region, about 38 individual SeaWiFS files were combined in each 15-day period, i.e. an average of 2.5 files per day.

As mentioned, SeaWiFS data are only available during low-cloud conditions, and hence there will be a positive correlation between data availability and low cloud conditions. If it is assumed that suspended sediment concentrations (and CDOM absorption) are higher when river flows are high, and that river flows increase rapidly after rainfall when clouds are present, then we may expect that SPM and CDOM absorption measured from space will have a negative bias i.e. we may underestimate true climatological values. An assessment of the magnitude by which we may underestimate SPM and CDOM absorption using ocean colour remote sensing was beyond the scope of the present study. However, compared with other issues affecting the quality of Case 2 products, especially regional variability in bio-optical properties of phytoplankton, sediment, and CDOM, this effect is unlikely to be significant.

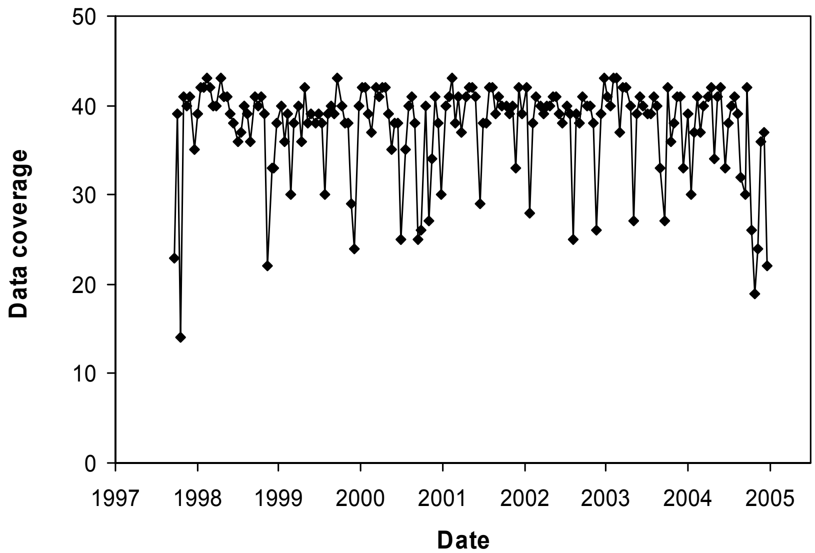

Figure 4: **Date coverage used in producing the climatological values. The value shown is the number of valid SeaWiFS files used in the analysis within a 15-day period.**

Following remapping, valid data were combined in log-space, i.e. the final output are log-averages of all the valid measurements at each pixel location. A log average is used as this will reduce the significance of occasional exceptionally high values on the overall average (Campbell et al. 1995).

The Marine Environment Classification (MEC) output domain was bounded by the following coordinates: 24°–57.5°S 157°E–167°W. The Case 2 data processing is carried out on the region bounded by the coordinates 25.5–55.5°S and 154.5°E–167.5°W. It was necessary to provide data for the output region not included in the Case 2 domain using the empirical method described previously in this report.

The data were finally remapped as a Mercator Projection. The final images for the MEC output domain are given in Figures 6 and 7 below. The data are supplied as both Heirarchical Data Format (hdf) and as ASCII text files. Latitude and longitude grids for the outputs are also supplied. The missing value identifier is defined to be “-9999”. This is included in the output file as an attribute. The distribution of sediment and

CDOM is typically considered to be approximately log-normal, and this is reflected in the value-frequency plots given in Figure 5.

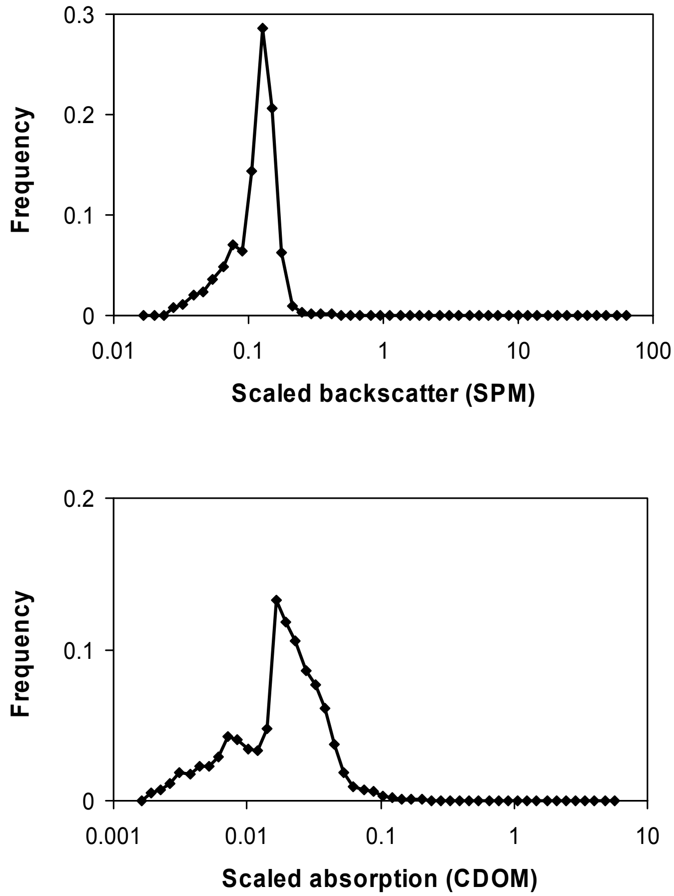

Figure 5: Frequency distribution of data in the output images.

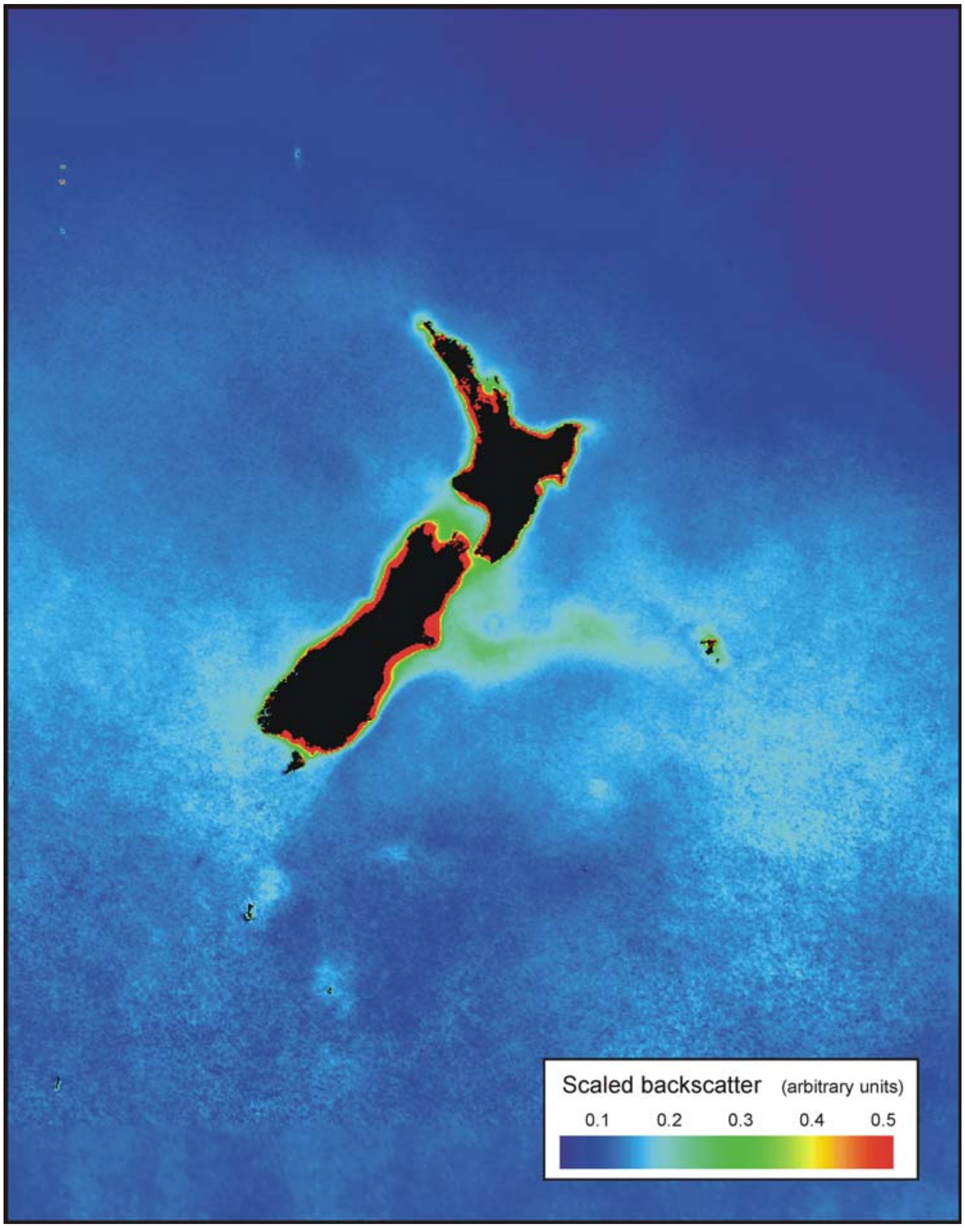

Figure 6: Scaled backscatter which is related to total suspended particulate material (SPM) concentration. The units are strictly arbitrary because of the unknown variations in SPM-specific backscatter with region and season, but approximate to g m^{-3}.

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