
Remote Sensing Survey of the Bay of Plenty: Report on Sea Surface Temperature and Ocean Colour product generation for Environment Bay of Plenty

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Prepared for

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NIWA Project: EBP04302

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Introduction

In April 2004, Environment Bay of Plenty (EBoP) contracted NIWA to deliver a range of remotely sensed Sea Surface Temperature (SST) and surface chlorophyll *a* (Ca) products to inform bio-physical numerical modelling efforts relevant to its Aquaculture Management Areas (AMA) project. The AMA project aimed to provide a predictive capability for the Bay of Plenty coastal system (see description and definitions of terms in Appendix 1). These products were:

1. Climatological monthly means and climatological monthly standard deviations for the EBoP coverage area based on NIWA 1 km spatial resolution AVHRR SST data for the period January 1993 to August 2004¹.
2. Three-day 1 km spatial resolution SST temporal composites for the same period.
3. Climatological monthly means and climatological monthly standard deviations for the EBoP coverage area based on NIWA 4 km spatial resolution case 1 (open ocean) SeaWiFS Ca data for the period September 1997 to August 2004.
4. Climatological monthly means for the EBoP coverage area based on NIWA 4 km spatial resolution case 2 (coastal ocean) Ca data, as generated by the NIWA Inherent Optical Properties (IOP) algorithm, for the period September 1997 to August 2004.
5. Three-day 1 km spatial resolution case 2 Ca composites (means) for the period defined in 1.

Bio-optical measurements in the Bay of Plenty were carried out to calibrate the NIWA IOP algorithm and hence enable the generation of case 2 products. These measurements were jointly funded by NIWA and EBoP. Case 2 Ca product generation was funded by NIWA, whereas other work (defined in 1, 2, and 3 above) was funded by EBoP.

The following report summarises the process of product generation, and provides a qualitative comparison of case 1 and case 2 Ca retrievals for the Bay of Plenty. It also provides an account of the BoP bio-optical research voyage and subsequent calibration of the IOP algorithm.

Generation of climatological SST products

The NIWA SST archive (NSA) comprises SST data for the EEZ beginning in 1993 at 1 km spatial resolution derived from Advanced Very High Resolution Radiometer (AVHRR) data which provide up to eight observations per day. Instantaneous SST retrievals in this dataset have a standard deviation error of $\sim 0.6^{\circ}\text{C}$, and a bias error less than $\pm 0.1^{\circ}\text{C}$. A Bayesian algorithm is used to detect cloud in the satellite radiances (Uddstrom *et al*, 2005 in press). Climatological monthly means, produced from monthly

¹ This was later extended to Mid-December 2004

composites of these data for this contract, used the Fourier decomposition methodology described in Uddstrom *et al*, 1999. Details of the NSA, cloud detection algorithm, SST retrieval equations, validation, and compositing method (to reduce the effects of cloud contamination) are also given by these authors.

An estimate of the climatological monthly standard deviations was generated by computing the standard deviation of the monthly anomalies. Anomaly means were typically close to zero, so it is unlikely that significant error was introduced by this approximation.

Generation of climatological SeaWiFS case 1 products

The SeaWiFS sensor on the seastar satellite, launched in September 1997, is owned and operated by Orbimage Inc. and delivers ocean colour data to NASA under contract. These data are publicly available at no cost for research purposes, but the owner charges for commercial uses of these data (e.g., by fishing companies). The contract for 1km data expired in December 2002, but was extended until early December 2004, after which only 4 km data are freely available for non-commercial use.

The New Zealand EEZ is observed about twice per day by successive overpasses around noon. The NIWA HRPT station in Wellington received direct broadcast 1km data from June 2000. Given the reduced number of observations relative to AVHRR, SeaWiFS composited data products are more prone to cloud contamination problems.

In-water constituents in the open ocean (so-called case 1 waters) are estimated using the SeaWiFS processing software SeaDAS using an empirical blue-green ratio algorithm. The (SeaWiFS) project target accuracy for chlorophyll retrievals in the open ocean is $\pm 35\%$, and achieving this required spatially extensive, long-term, high quality calibration and validation data. The vicarious calibration data were derived from an extensive database of shipboard bio-optical measurements, but little of this came from the New Zealand region. The Southern Ocean is also under-represented in this dataset. NIWA validation efforts (e.g., Richardson *et al*. 2004, Pinkerton *et al*. 2005) have demonstrated that there are region-dependent biases of up to 20 - 30% in end-to-end SeaWiFS Ca retrievals.

Generation of case 1 climatological monthly means and standard deviations proceeded as described for SST above, except that a larger number of Fourier harmonics was required to adequately represent the more complex Ca annual cycle, and the standard deviation filter (Uddstrom & Oien, 1999) used in the compositing algorithm was increased to accommodate the approximately log-normal statistics of chlorophyll (remotely sensed or in situ).

Bio-optics Research Voyage EBoP0604 and IOP Algorithm development

Conditions at the time of the cruise were suitable for bio-optical measurements of this type – calm weather after a wet and stormy period facilitated high quality bio-optical measurements of a wide range of bio-optical conditions. Bay of Plenty waters sampled during this period were typically turbid, with low C_a concentrations and high detrital absorption. Concentrations of SPM spanned 2 orders of magnitude (0.3 – 30 g m⁻³), CDOM absorption varied by almost the same amount (0.02 – 1.2 m⁻¹), whereas C_a concentrations were relatively low throughout (0.4 – 1.6 mg m⁻³).

Measurements have led to modifications of a satellite processing algorithm (Moore and Aiken 2004) for the Bay of Plenty region. Total suspended particulate matter (SPM) concentration was well correlated with CDOM absorption. This is to be expected if both sediment and terrigenous CDOM are introduced into the coastal zone by river discharge, and sediment re-suspension processes are not significant. Specific absorption of particulate detrital material in the Bay of Plenty was generally much higher than found elsewhere around New Zealand to date (Golden Bay, Tasman Bay, Marlborough Sounds), and elsewhere in the world (English Channel, German Bight, Mediterranean Sea). The spectral shape of absorption by sediment was indistinguishable from that of CDOM, as is typical for organic rich, fine-grained suspended sediments such as those of the Bay of Plenty. We treated the SPM and CDOM together, and estimated their combined absorption at 490 nm from the backscattering signal. This absorption was removed from the total absorption at 490 nm to give absorption due to phytoplankton. Phytoplankton absorption at 490 nm was scaled by the chlorophyll specific absorption coefficient to estimate C_a .

Our measurements were dominated by stations where there were low concentrations of chlorophyll compared to high concentrations of sediment and CDOM, and estimation of C_a under these conditions tends to be imprecise. Further fieldwork to characterise the bio-optical conditions of phytoplankton-dominated waters in the Bay of Plenty (e.g. in the spring) and to validate the algorithm would improve the robustness of the satellite measurements of C_a near the coast. A more detailed exposition of the Bio-optics Research Voyage EBoP0604 and subsequent calibration of the NIWA IOP algorithm are given in Appendix 2

End-to-end comparison of in-situ measurements with satellite observations was not possible given the absence of clear-sky co-temporal SeaWiFS observations or of an in-situ time-series. However, it is possible to get some feeling for the quality of the NIWA IOP algorithm case 2 product by comparing with equivalent case 1 chlorophyll retrievals (OC4v4) on a pixel by pixel basis (Figure 1). Two regions have been defined. One is restricted to offshore, low-SPM conditions. The other encompasses both offshore (low SPM) and near shore (relatively high SPM) waters.

As expected, the case2:case1 difference is negative when SPM is estimated to be high. In open ocean waters, there is a positive bias. Richardson *et al* 2004 and Pinkerton *et al* 2005 demonstrate that in open oceanic waters around New Zealand, the case 1 OC4v4 chlorophyll algorithm tends to underestimate in situ measurements by 20-30%. The overestimate by the case 2 algorithm chlorophyll product in case 1 waters is therefore likely to be smaller than Figure 1 suggests.

Generation of SeaWiFS case2 products

The NIWA IOP algorithm iteratively solves a set of non-linear equations both to correct satellite radiances over waters with significant non-phytoplanktonic sediment concentrations for the dominant atmospheric signal, and to retrieve IOPs from corrected water leaving radiances. It is therefore significantly slower than the standard SeaDAS case 1 algorithm. Given that the BoP calibration is local (see above and Appendix 2) and that processing 5 years of SeaWiFS 4km data and more than 1 year of 1km data would have been time-consuming, the L1A (top-of-atmosphere radiance counts) data was subset to the BoP area before processing to products (e.g., Ca). Consequently, Ca products often have consecutive missing days where there are no observations of the region – typically because of cloud contamination. This problem is still evident in the case 2 three day composites, presumably during long spells of inclement weather.

Generation of case 2 three day (1 km) and monthly (4 km) composites, and monthly climatologies and standard deviations is as described above for the SST and case 1 chlorophyll.

The climatological case 1 and 2 chlorophyll products provide further insight into the quality of the NIWA IOP algorithm retrievals. Figure 2 shows the climatological case 2 monthly means, and Figure 3 contains images showing the difference between case 1 and case 2 chlorophyll in the BoP. There are significant biases in case 1 chlorophyll (relative to case 2) in regions close to the coast between August and November, which seems reasonable given the higher sediment concentrations observed near river mouths during the optics cruise (see Appendix 2). Differences away from the coast are predominantly negative, in agreement with the trend evident in Figure 1. We conclude that although a quantitative estimate of errors from NIWA IOP algorithm case 2 chlorophyll retrievals is not possible until further bio-optics research and validation work have been done in the BoP, there is likely to be good qualitative information on the distribution of surface chlorophyll in this product, and on the regions where case 2 conditions are important.

Three day composites of case 2 chlorophyll exhibited what appear to be algorithmic instabilities in a small number of cases. The reason for this is not known at the moment, but is under investigation. From the comparison of case 1 and case 2 climatological products, it does not appear to cause a major bias, although it may contribute to the negative bias of the case 1 (relative to case 2) chlorophyll product in the open ocean evident in Figure 1 and Figure 3.

References

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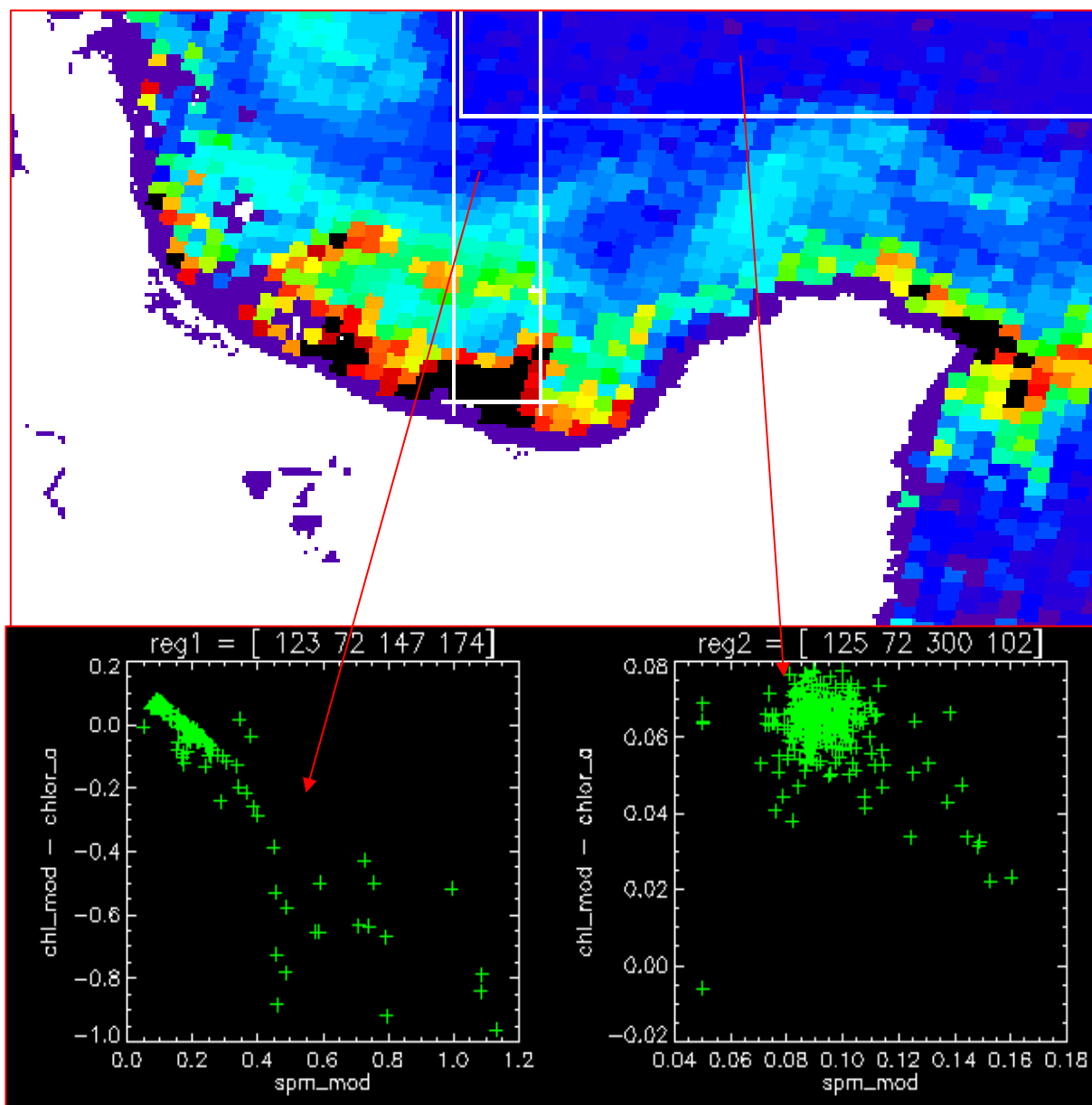


Figure 1: Comparison of the difference between case 2 (chl_mod) and case 1 (chlor_a) chlorophyll as a function of SPM retrievals (spm_mod) for pixels within the two rectangular regions overlaid on the relatively cloud-free SPM overpass of the BoP for January 5, 2004

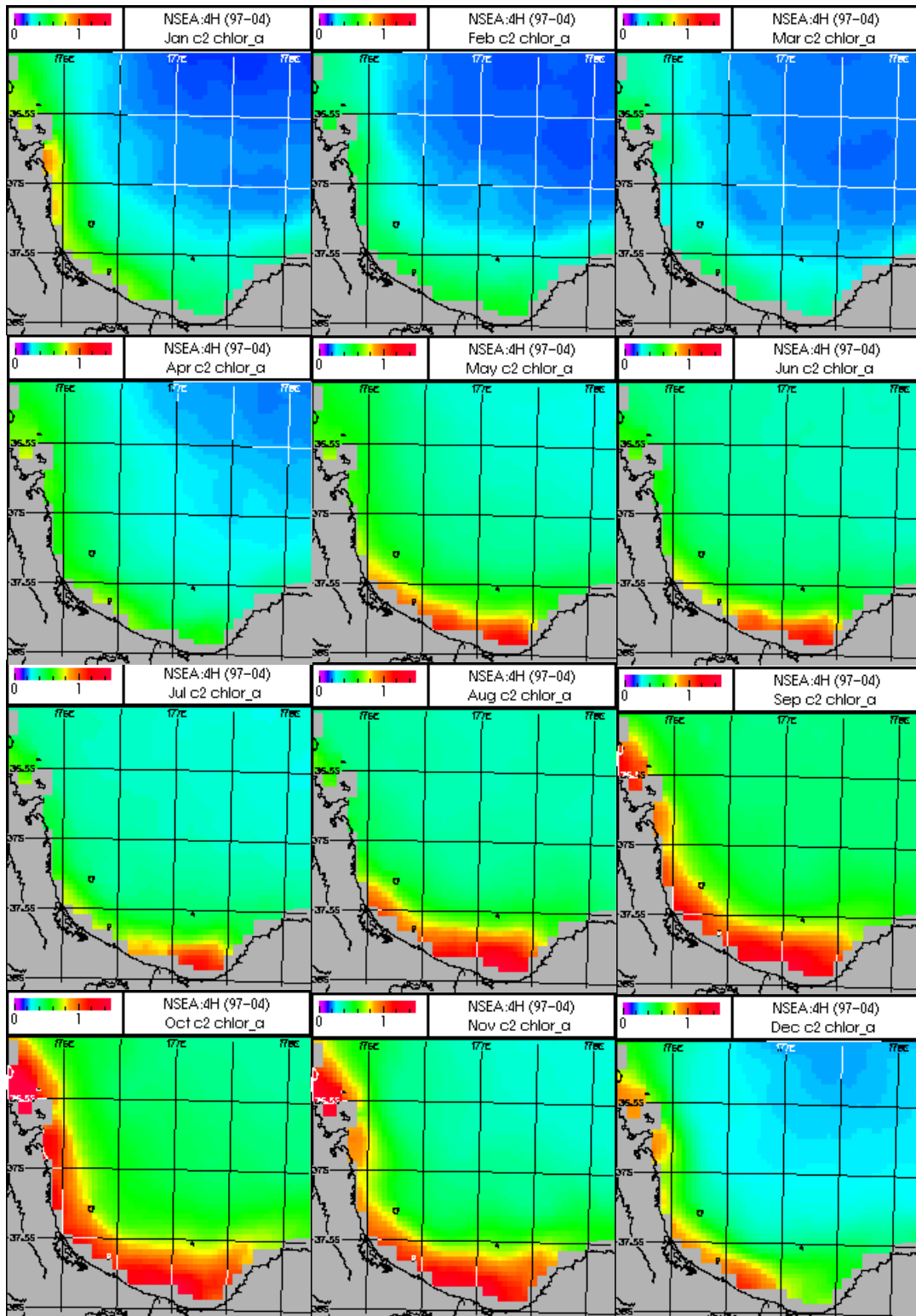


Figure 2 Climatological monthly case 2 chlorophyll composites for the BoP area.

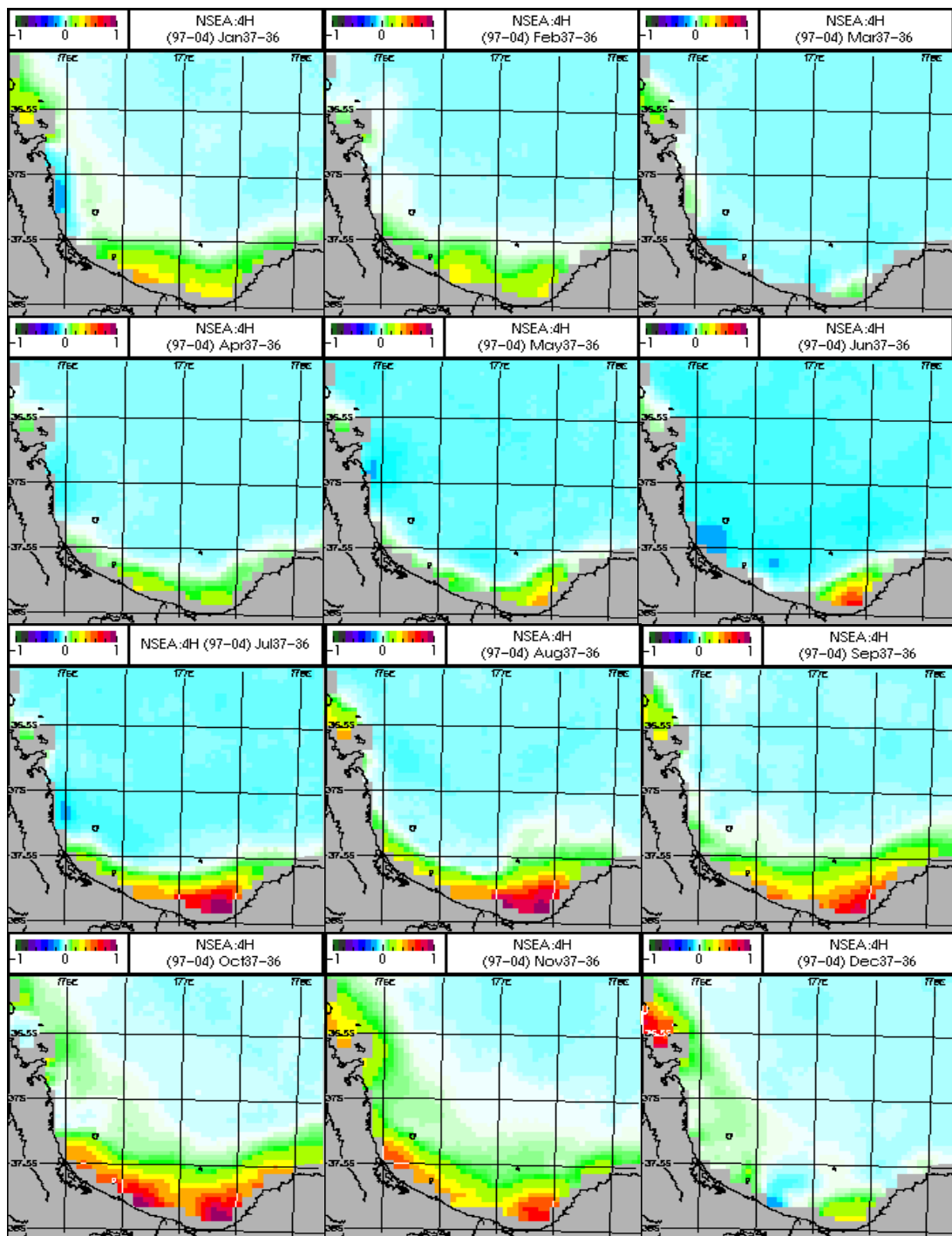


Figure 3: Differences between case 1 and case 2 (c1-c2) climatological monthly means. Differences away from the coast are largely negative, in agreement with the trend evident in Figure 1.

Appendix 1

Remote sensing survey of Bay of Plenty: Contract

	Contracting Party	Authorised Signature	Print Name	Date
BETWEEN	EBoP (the Client) and ASR Ltd (the Subcontractor)			
AND	NIWA (the Data and Service Provider)			

Definitions

Unless otherwise stated, the following definitions apply for the purposes of this contract:

Month is calendar month.

Data products are AVHRR Sea Surface Temperature (SST), or SeaWiFS case 1 (OC4v4) and case 2 (NIWA IOP algorithm) chlorophyll-a concentration, and their statistical derivatives.

Climatological monthly mean or standard deviation Data products at a given location in the coverage area are the mean or standard deviation of Data products, calculated for the given month from the Fourier decomposition of the seasonal cycle contained in the whole time series record of satellite observations, at the given location.

Monthly or three-day mean Data products at a given location in the data coverage area are means of all Data products observed within specified disjoint monthly or three-day intervals at that location.

A Data product **monthly anomaly** is the difference between the observed and expected value of a Data product at a given location for a given month.

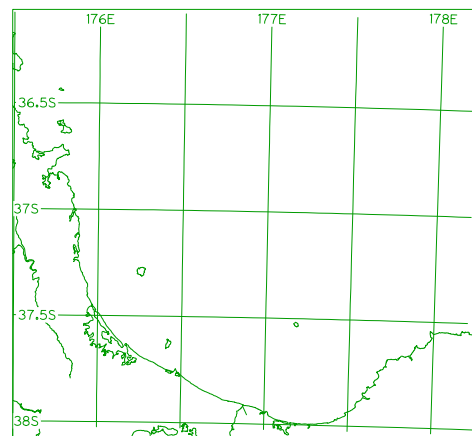


Figure 4: Data analysis area

The **NetCDF** file data format is documented at <http://my.unidata.ucar.edu/content/software/netcdf/index.html>

The data **coverage area** for 1km spatial resolution Data products is shown in Figure 4 (a Lambert Conformal map projection, having average pixel resolution: 1089 m², and standard parallels at -36.7°S and -37.4°S). The map projection for 4km spatial resolution Data products is identical except that resolution is lower (average 4356 m) i.e., ¼ the resolution of the 1km mapped Data)³.

The **NIWA IOP** algorithm is the retrieval algorithm used by NIWA to estimate the chlorophyll-a concentration Data product from water leaving radiances in case 2 (coastal) waters.

A **File** is a binary NetCDF disk file in which the Data products will be stored on the NIWA ftp server for downloading by EBoP and/or its Subcontractor.

The **Client** is Environment Bay of Plenty (EBoP), whose details are given in Section 0.

The **Subcontractor** is ASR Ltd, whose details are given in Section 0.

The **Data** refers to Section 0.

3DD is the hydrodynamic/primary productivity numerical model developed by the Subcontractor

The **project** is the Client's Aquaculture Management Areas (AMA) project

Description of Data and Services

AVHRR SST Data (1km spatial resolution)

Climatological monthly means, and climatological monthly standard deviations (approximated via the standard deviation of the monthly anomalies), for the coverage area based on NIWA SST Data for the period January 1993 to August 2004⁴ (as available) will be generated and output in NetCDF format.

Three-day means for the period June 2003 – August 2004 for the coverage area will also be supplied.

This work is to be part-funded by EBoP. The cost to EBoP is \$10K (+GST), and delivery will begin within 2 months of the contract start date. NIWA will fund the development and processing of the climatological and three-day composited products.

SeaWiFS chlorophyll-a concentration Data (4 km spatial resolution, case 1 retrieval algorithm)

Climatological monthly means for January-December, and climatological monthly standard deviations (approximated via the standard deviation of the monthly anomalies),

² Hence the conventional name “1km” spatial resolution. Each pixel actually references an area of about 1 km² at nadir. Similar remarks apply to “4km” spatial resolution data.

³ Data product and location (latitude, longitude) will be provided for each pixel in the coverage area.

⁴ That is, NIWA will provide 12 climatological monthly means, and 12 climatological monthly standard deviations for each pixel in the coverage area.

for the coverage area will be generated using the case 1 OC4v4 retrieval algorithm⁵. The Data coverage period will be September 1997 to August 2004 (as available) inclusive.

This work is to be part-funded by EBoP. The cost to EBoP is \$10K (+GST), and delivery will begin within 2 months of the contract start date. NIWA will fund the development and processing of the climatological product.

Bay of Plenty bio-optical validation measurements and algorithm development.

NIWA will carry out 5 days of measurements with NIWA instruments and personnel under conditions acceptable for such work, provide an analysis of the Data, and generate a local calibration for the NIWA IOP algorithm.

The measurements will be carried out (subject to staff availability) in autumn/early winter. The analysis and algorithm development work will be completed within 3 months of completing the measurements.

This work is joint NIWA-EBoP funded. The cost to EBoP will be \$35k in addition to all vessel and vessel-related costs.

SeaWiFS chlorophyll-a concentration Data (4 km spatial resolution, case 2)

The Data will consist of climatological monthly mean data for the coverage area. As the case 2 processing will depend on results from the local bio-optical validation, delivery of Data products will begin no later than 2 months after completion of the analysis of fieldwork Data and case 2 algorithm development work (as specified in section 0).

The cost of this processing, including the development of non-standard climatological products, is funded entirely by NIWA.

SeaWiFS chlorophyll-a concentration Data (1 km, case 2)

The Data will consist of files containing 3-day means for the coverage area during the period June 2003 – August 2004 (as available) inclusive.

These Data products will be available no later than 3-4 months after completion of the analysis of fieldwork Data and NIWA IOP algorithm development work (as specified in section 0). The cost of this work, including the development and processing of non-standard 3-day composites, is funded entirely by NIWA.

Terms and conditions for access to NIWA Data

- i. NIWA grants the Client the non-exclusive, non-transferrable copy of the Data.
- ii. The Client hereby acknowledges that it will only have access to, or receipt of, the Data on the following conditions:
 - The Client will ensure that any employees or subcontractors, who are engaged for the purpose of this project and who will have access to NIWA's data, are also subject to the following conditions.

⁵ Note that NIWA does not expect the OC4v4 retrieval algorithm to provide accurate estimates of surface chlorophyll concentration in case 2 waters.

- The Client may only make or receive one copy of any item of Data. The Data shall only be used by the Client for the Purpose – as set out below – for which it has been provided. No Data may be stored, reproduced or used for any other purpose. No Data may be disclosed to or used by any person other than the Client and its Subcontractor engaged for the purpose of this project, without the prior written consent of NIWA. The Data may not be released, published, reproduced, sold or otherwise traded except pursuant to such written consent.
- The copyright and all other intellectual property rights in the Data remain vested solely in NIWA. The Client's access to or receipt of the Data does not vest in the Client any rights other than to such access or receipt.
- NIWA makes no representations or warranties regarding the accuracy of the Data, the use to which Data may be put or the results to be obtained from the use of the Data. Accordingly NIWA accepts no liability for any loss or damage (whether direct or indirect) incurred by any person through the use of or reliance on the Data, and the Client shall bear and shall indemnify and hold NIWA harmless from and against all losses, claims, demands, liabilities, suits or actions (including reasonable legal fees) in connection with access and use of NIWA's Data to whomever or how so ever caused.
- NIWA must be satisfied with the scientific integrity of the analyses conducted by EBoP or its Subcontractor.
- NIWA is to be acknowledged in publications (relating to the Data), produced by the Client. NIWA's logo or an appropriate credit shall be clearly shown adjacent to any figure etc. where the Data are presented or used to reach a conclusion by the Client or Subcontractor

Purpose

Use of these Data will be restricted solely to the Client's Aquaculture Management Areas (AMA) project, and is limited to:

1. Determining the temporal variations in 3-day mean 1km SST and case 2 chlorophyll concentrations between June 2003 and August 2004 in the coverage area and spatial patterns (such as bloom events) therein.
2. Comparison of the results from these analyses with predictions from the 3DD model (sea surface temperature and surface chlorophyll-a concentrations).
3. Outputs consistent with the SeaWiFS project requirement of non-commercial data use⁶.
4. In order to facilitate the use of the Data and to stimulate collaboration, joint scientific review meetings between mutually agreed representatives of NIWA, EBoP, and the Subcontractor should take place at intervals of not greater than 3 months throughout the AMA project.

Duration

The AMA project runs from July 2003 through to December 2005. Field sampling to obtain data on water quality parameters, nutrients and plankton abundance, and species identification will be obtained throughout the water column at set points along three transects across the coastal shelf waters of the Bay of Plenty once in each season of the year. Current measurements and depth integrated temperature measurements will be recorded at a number of points during the period of field sampling. The field sampling will run over a period of one year from September 03 to August 04.

⁶ See http://seawifs.gsfc.nasa.gov/SEAWIFS/ANNOUNCEMENTS/APPENDIX_B.html

Field results and remote sensing data (set out in this contract) will be used to describe temporal/spatial oceanography/productivity patterns and to refine the development of numerical models aimed at providing a predictive capability for the Bay of Plenty coastal system.

The Data will be available for this work until the end of 2005, after which the original and all copies and derivatives must be destroyed.

Details of Contracting Parties

Data and Service Provider

Name	National Institute of Water and Atmospheric Research (NIWA)
Principal location of business	301 Evans Bay Parade, Greta Point, Kilbirnie Wellington
Mailing address <i>(if different from above)</i>	P.O. Box 14901, Kilbirnie, Wellington
Phone	
Fax	
Email	

Client

Name	Environment Bay of Plenty (EBoP)
Principal location of business	5 Quay St Whakatane
Mailing address <i>(if different from above)</i>	P.O. Box 364 Whakatane
Phone	0800 368 267
Fax	0800 368 329
Email	Stephen.park@envbop.govt.nz

Subcontractor

Name	ASR Ltd
Principal location of business	P.O Box 13048 Hillcrest Hamilton
Mailing address <i>(if different from above)</i>	1 Wainui Rd Raglan
Phone	07 825 0380
Fax	07 825 0386
Email	k.black@asrltd.co.nz

Appendix 2

Bio-optics Research Voyage *EBoP0604* supporting Ocean Colour Remote Sensing of the Bay of Plenty

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6 September 2005
NIWA Project: EBP04302

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Executive Summary

Work co-funded by NIWA and Environment Bay of Plenty (EBoP) has produced satellite remotely-sensed observations of chlorophyll-a concentration to assist management of marine resources in the Bay of Plenty. The work involved two stages:

I. Bay of Plenty bio-optical validation measurements and algorithm development. NIWA personnel carried out 6 days of bio-optical measurements in the Bay of Plenty region in June 2004. EBoP provide the research vessel (Port Whakatane II), crew, personnel during sampling, logistic support, and the EBoP laboratory in Whakatane as a base-station. Bio-optical measurements were made at 24 coastal stations between the Motu River and Tauranga. These data have been used to produce a modified processing algorithm specific to the Bay of Plenty region.

II. Integration of the local Bay of Plenty bio-optical algorithm into the NIWA satellite data processing system.

The results are summarised below.

1. Suspended sediment and dissolved detritus in the Bay of Plenty are the major causes of error in satellite measurements of chlorophyll-a in the coastal zone. Conditions at the time of the cruise were excellent for bio-optical measurements – calm weather after a wet and stormy period facilitated high quality measurements of a wide range of sediment and detrital concentrations. Bay of Plenty waters sampled during this period were typically turbid, with high particulate and detrital loads: suspended particulate material (SPM) concentration: 0.3–30 g m⁻³; Coloured dissolved organic matter absorption at 440 nm: 0.02–1.2 m⁻¹. Chlorophyll-a concentrations were relatively low throughout (0.4–1.6mg m⁻³).
2. Suspended sediment in the Bay of Plenty absorbed light more strongly than is typically found elsewhere around New Zealand to date (Golden Bay, Tasman Bay, Marlborough Sounds), and elsewhere in the world (English Channel, German Bight, Mediterranean Sea).
3. High sediment loads caused the normal satellite ocean colour processing methods to overestimate chlorophyll by more than a factor of 2. Total absorption must be corrected for absorption due to suspended particulate material in order to estimate chlorophyll concentration in the Bay of Plenty.
4. Measurements have led to modifications of a satellite processing algorithm (Moore and Aiken 2004) for the specific properties of the Bay of Plenty region.
5. Tests using the in situ measurements show that the new algorithm provides estimates of chlorophyll-a that are unbiased at the 95% confidence level (bootstrap analysis).

6. Note that the performance of the modified algorithm in other periods of the year, when bio-optical properties may significantly differ from those experienced during the field survey, remains to be determined. In particular, measurements when high concentrations of chlorophyll-a ($>2 \text{ mg m}^{-3}$) are present would be useful to improve the algorithm. It is recommended that future bio-optical surveys in other seasons, and long-term monitoring observation of key in water biogeochemical properties be conducted. These will validate and improve the quality of ocean colour remote sensing datasets of the Bay of Plenty for medium and long-term monitoring and management.

Introduction

Satellite remote sensing of ocean colour offers the capability to map distributions of coloured water constituents over scales (spatial: 1–100 km; temporal: 1–5000 days) appropriate to the monitoring and management of coastal resources. The most commonly estimated water constituent is the concentration of chlorophyll-a (C_a), which is typically used as a proxy for phytoplankton abundance. Methods of estimating C_a in oceanic waters from satellite ocean colour measurements 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 ($>2 \text{ mg m}^{-3}$) in the water can lead the atmospheric correction method to fail and lead to invalid estimates of water constituents. Methods to correct for atmospheric effects over turbid waters (e.g. Moore *et al.* 1999; Lavender *et al.* 2004) have been implemented. Their validation forms the basis of ongoing research by the authors, but is not addressed directly by this work as they are assumed to vary little with region. Second, simple band-ratio algorithms that estimate C_a from measurements of ocean colour (e.g. SeaWiFS OC4v4 algorithm, O’Reilly *et al.* 2000) fail in the presence of coloured material not of local phytoplankton origin (such as suspended sediment and/or dissolved yellow substance from land run-off: Aiken *et al.* 1995). These are known as “Case 2” waters (Gordon and Morel 1983). In contrast, “Case 1” waters are those (typically oceanic) waters where the water colour depends solely on phytoplanktonous material.

Although there are a number of Case 2 algorithms currently in use worldwide (e.g. Moore and Aiken 2004; Carder *et al.* 2003; Doerffer and Schiller 1997), there are specific regional characteristics that require development and validation. This paper uses a remote sensing Case 2 “Inherent Optical Property” (IOP) algorithm, based on that described by Moore and Aiken (2004). The IOP algorithm estimates bio-optical properties of water constituents from ocean colour measurements when phytoplankton, suspended sediment and/or dissolved yellow substance co-occur. The algorithm has two steps: first, it estimates the inherent optical properties of the water column; second, it uses these IOPs to estimate the bio-geophysical parameters: C_a , total suspended particulate matter (SPM) concentration, and the absorption of coloured dissolved organic matter (CDOM). Since the Moore and Aiken (2004) IOP algorithm was developed using data measured predominantly in the coastal waters of Europe, its performance and application to other coastal water masses - such around New Zealand - remains to be determined.

Case 1 – Case 2 Operational Definition

Case 2 waters were defined by (Mueller *et al.* 2002a) as those which have $a_g(380) > 0.1 \text{ m}^{-1}$, and/or an SPM concentration $> 0.5 \text{ g m}^{-3}$. The former is approximately equivalent to $a_g(440) > 0.035 \text{ m}^{-1}$ (Kirk 1994). As an indicator of Case 2 water for SeaWiFS data, Lavender *et al.* (2004) suggested using a threshold equivalent to $R_{rs}(510) > 0.0038 \text{ sr}^{-1}$ and $R_{rs}(670) > 0.0036 \text{ sr}^{-1}$. These reflectance thresholds correspond to an SPM concentration of

$\sim 0.8 \text{ g m}^{-3}$ in low to moderate phytoplankton abundances ($C_a < 5 \text{ mg m}^{-3}$; Bale *et al.* 1994).

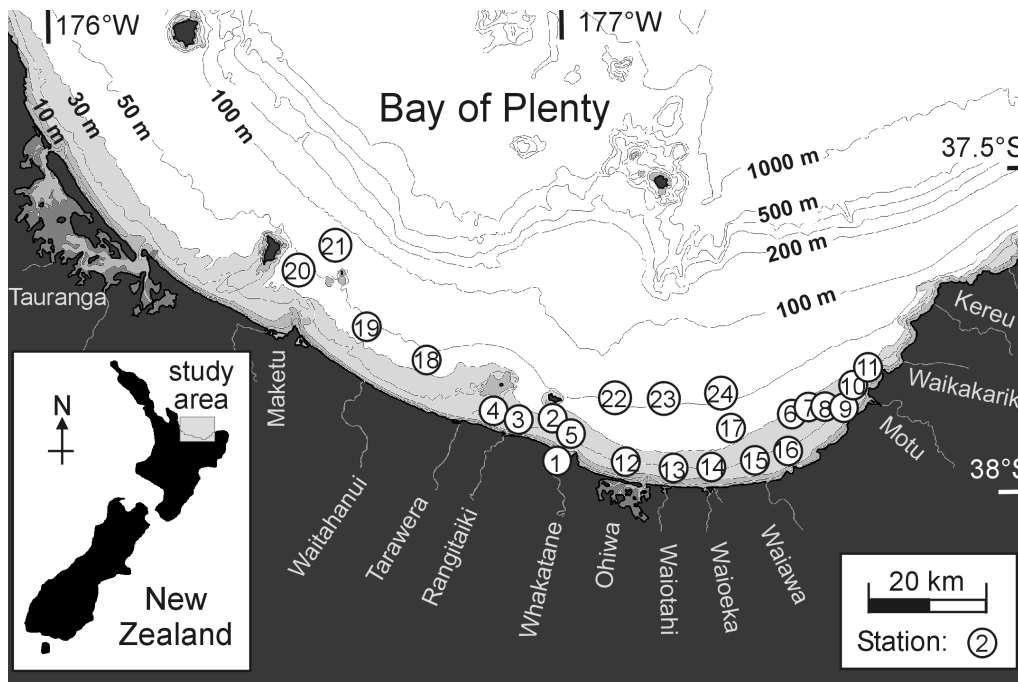


Figure 5: Location of stations for EBoP0604

Here, we define Case 2 waters as those satisfying any of the above constraints.

Study Area and Stations

All research was carried out from the research vessel *Port Whakatane II*, from Whakatane, Environment Bay of Plenty, between 4 – 13 June 2004. Measurements were made at 19 stations, east from Whakatane to the Motu River, and west to Okurei Point (Figure 5).

The IOP-algorithm

The Inherent Optical Property (IOP) algorithm was first presented by Moore and Aiken (2004). We consider only the implementation of the algorithm that may be used to process ocean colour measurements from the NASA SeaWiFS sensor (Hooker *et al.* 1992).

Remote measurements of water-leaving radiance (L_w) by SeaWiFS are normalised by irradiance incident on the sea surface and corrected to a standard viewing geometry to give the remote-sensing reflectance, R_{rs} (sr^{-1}). See Table 1 for acronyms and symbols used in this work. SeaWiFS measures R_{rs} in six spectral bands through the visible part of the spectrum which constitutes a single measurement of “ocean colour”. SeaWiFS visible spectral bands are centred on 412, 443, 490, 510, and 555 nm. This work was primarily concerned with the in water part of the processing, and we take R_{rs} as the starting point. The accuracy of the remote measurement of R_{rs} in Case 1 waters has had a preliminary validation in the vicinity of

New Zealand (Richardson *et al.* 2003; Pinkerton *et al.* 2004b) which supports work carried out by NASA indicating that SeaWiFS is achieving its target accuracy of measurement of R_{rs} $\pm 5\%$ absolute (i.e. relative to a traceable standard) and $\pm 1\%$ relative between bands off Hawaii (Hooker *et al.* 1992; Eplee *et al.* 2001). The accuracy of SeaWiFS measurements of R_{rs} in New Zealand Case 2 waters forms ongoing work at NIWA.

The in-water part of the IOP algorithm has two parts. In the first part, the remote measurements of ocean colour are used to estimate the inherent optical properties of the water column. In the second part, these IOPs are used to estimate bio-geophysical parameters. The details of the model are given in Moore and Aiken (2004), and Pinkerton *et al.* (2004a), and will not be repeated here. It is known that the relationships between inherent optical properties and biogeochemical variables are often highly variable between different bio-optical provinces. They depend on, amongst other factors: phytoplankton species composition, the nature of inorganic sediment (e.g. particle size distribution, particle shape, and the refractory or labile nature of the particulate material), and the nature of the catchment area for land run-off (e.g. Bale *et al.* 1994; Bricaud *et al.* 1995; Babin *et al.* 2000). By changing a relatively small set of coefficients, the algorithm structure allows us to “tune” the processing to better reflect local bio-optical conditions.

Methods

In situ measurements

The objectives of the voyage were to measure the bio-optical properties of the waters in the Bay of Plenty in order to improve the ability of in-water ocean colour remote sensing algorithms to estimate the constituents of the water column. This was done by making four, co-incident sets of measurements at each station:

- Apparent Optical properties: Radiometric measurements of the above-surface and underwater light field were made to obtain water leaving radiance, incident irradiance, diffuse attenuation, R_{rs} .
- Inherent Optical properties: spectral absorption, total scattering, backscattering, and beam attenuation coefficients of the water column as a whole, and of individual coloured materials in the water.
- Bio-geophysical properties. Water samples from 2 depths within the first attenuation depth (at 490 nm) were collected using a Nisquin bottle. The optically-active constituents of these water samples were analysed in the laboratory following Mueller *et al.* (2002b) for concentration of suspended particulate material, phytoplankton pigment concentration, particle size distribution, phytoplankton assemblage taxonomy.

- Vertical water column structure and other ancillary information to aid interpretation of other measurements: conductivity profile, temperature profile (both using the CTD of the BioFish (<http://www.niwa.cri.nz/pubs/wa/10-4/biofish>), cloud cover, sea-state, wind speed and direction.

The time difference between the entire suite of measurements was minimised to ensure that the measurements relate to the same parcel of water.

Radiometric Measurements

Underwater optical measurements were made using a Satlantic Multichannel Profiling Radiometer (SPMR) (Satlantic Inc, Canada). The system was designed to adhere to specifications given by Mueller and Austin (1995), revised by Mueller *et al.* (2002a,b), and has been widely used for validation and algorithm development work by research groups around the world (e.g. Aiken *et al.* 2000; Stramska *et al.* 2000; Siegel *et al.* 2003). The SPMR was floated away from the shadow caused by the ship and descended under its own weight for ~100 m measuring depth, instrument inclination to the vertical, downwelling irradiance (E_d , $\mu\text{Wcm}^{-2}\text{nm}^{-1}$) and upwelling radiance (L_u , $\mu\text{Wcm}^{-2}\text{nm}^{-1}\text{sr}^{-1}$) in seven narrow (10 nm wide) spectral bands at the rate of 10 samples/m. The SPMR spectral channels were centred on 412, 443, 490, 510, 555, 665 and 683 nm. The five visible channels are aligned exactly with SeaWiFS bands 1-5. Channels 6 and 7 are not considered in this study. An average of three profiles (or “casts”) per station were measured. A second Satlantic radiometer was mounted in an unshaded position on the ship superstructure and measured above-surface incident irradiance (E_s , $\mu\text{Wcm}^{-2}\text{nm}^{-1}$) in the same spectral bands as the SPMR.

The SPMR radiometers were calibrated immediately before the research voyage by Satlantic using calibration standards traceable to the US National Institute of Standards and Technology. All processing of radiometric data was compatible with the SeaWiFS protocols (Mueller and Austin 1995; Mueller *et al.* 2002a,b).

Least squares bisector (Model 2) regression in log-normal light-depth space was used to fit a depth-independent diffuse attenuation coefficient $K_d(\lambda)$ to the data where this was appropriate. The coefficients of determination (R^2) for the log-linear regressions was >97% on average. The diffuse attenuation coefficients were used to estimate $L_u(\lambda)$ just below the water surface. The propagation of upwelling radiance through the water surface was taken as spectrally constant and computed as in (Gordon *et al.* 1988; Mueller *et al.* 2002a). Remote sensing reflectance was calculated as: $R_{rs}(\lambda) = L_w(\lambda) / E_s(\lambda)$.

Variation between subsequent optical casts was often considerable, and reflects a combination of a number of factors, including patchiness of coloured material in the water (heterogeneity on scales of between ~10 m and 100 m), and the sensitivity of the measurement and optical data processing system to varying environmental factors during measurements, such as incident lighting conditions, instrument attitude variations, surface roughness effects. The mean variation between measurements of R_{rs} on individual cast and the station average values

was 20% for 490 nm and this may be taken as an indication of the uncertainty in each measurement of R_{rs} .

The SPMR instrument radius was 0.05 m, and it was necessary to correct water-leaving radiance values (L_w) for instrument self-shading at every station (Gordon and Ding 1992; Mueller *et al.* 2002a). Self-shading reflectances were calculated based on in situ measurements of absorption (described below). The correction factors were greatest at the blue bands where absorption was highest, and varied between 4 and 185% for the 412 nm band. At the red end of the spectrum (555 nm), the self-shading correction was between 1 and 13%. Across the six radiometric bands, the average corrections were 25, 15, 8, 6, and 3% (respectively). There is some uncertainty (~20%) in these corrections arising from uncertainties in the absorption measurements, uncertainties in the value of E_{sky}/E_s used, and the fact that there has been only limited experimental verification of the method of calculating the self-shading correction (Zibordi and Ferrari 1995).

Phytoplankton Pigments

Water samples were filtered onto a 25 mm Whatman GF/FTM filter under subdued light conditions at a shore station, typically within 4 hours of water collection. The filters were folded, blotted three times to remove excess moisture, placed in cryovials, and snap frozen in liquid nitrogen. Frozen samples were stored in the dark at -20°C until analysis within 8 weeks of sampling. Pigments were extracted into 3 ml of 90% acetone by unfolding the filter, cutting into strips, probe sonicating for 30 sec and soaking at -20°C over a 4 h period. All procedures were carried out under subdued light conditions. The extract was analysed for phytoplankton pigment concentration by two methods: fluorometrically and by High Performance Liquid Chromatography. Chlorophyll-a concentration determined by the fluorometric method following the procedure of Strickland and Parsons (1968). The HPLC analysis followed the procedure of Zapata *et al.* (2000). Pigments were quantified at 436 nm based on calibration using commercially available standards for chlorophyll-a, chlorophyll-b, lutein and BB-carotene (Sigma Chemicals Inc.). Other pigments were quantified using published extinction coefficients (Wright and Mantoura 1997). Total chlorophyll-a concentration was calculated as the sum of chlorophyll-a and derivatives (monovinyl and divinyl chlorophyll-a, chlorophyllide-a, chlorophyll-a allomers and epimers).

In all cases, HPLC measurements showed that chlorophyllide-a concentration were <3% of C_a , indicating that samples were preserved effectively between the time of collection and subsequent analysis. In the subsequent analysis, we use HPLC-determined values (following Mueller *et al.* 2002b).

Absorption measurements

Water samples were filtered onto a 25 mm Whatman GF/FTM filter in subdued light conditions at a shore laboratory within typically 6 hours of water collection. The filters were placed face up in covered Petri-dishes, frozen and stored in the dark at -20°C until analysis

within 4 weeks of sampling. The filters were analysed for the absorption of particulate material using the “filter-paper method” (Mitchell and Kiefer 1988). The filters were scanned at 2 nm bandwidth using a dual-path Jasco 7850 UV/VIS spectrophotometer with integrating sphere, before and after bleaching by 0.1% active chlorine solution (sodium hypochlorite). These absorptions correspond to $a_{ph}+a_d$ and a_d respectively. The difference between the unbleached and bleached absorptions gives absorption by phytoplankton pigments a_{ph} . Optical pathlength amplification effects were corrected using the procedure of Mitchell and Kiefer (1988) and the coefficients of Cleveland and Weidemann (1993).

Absorption by CDOM was measured by filtering water samples through a 0.22 μm membrane filter using clean, non-leaching, low-vacuum filtration equipment. Baseline checking followed Mueller *et al.* (2002b). Duplicate optical pure water blanks were used to check for coloured material being “leached” from the bottles themselves (Mueller *et al.* 2002b). An exponential function following (Bricaud *et al.* (1981) was fitted to the data using least squares regression to estimate the slope factor, S , and $a_g(440)$. Coefficients of determination were always $R^2 > 0.95$.

Suspended Particulate Material

Immediately following the voyage, gravimetric suspended matter concentration was obtained by the differential weighing of a pre-combusted 0.7 mm diameter glass fibre filter (Whatman GF/FTM) before and after filtration of ~ 4 litres of sample (Strickland and Parsons 1968; Van der Linde 1998). Salt was removed prior to drying by triplicate washing in distilled water. Subsequent combustion of the filters (500°C, 4 h) and weighing, gave the organic matter content of the sediment.

In situ absorption-attenuation measurements

The absorption-attenuation meter (AC-9, Wetlabs Inc.) is a high precision optical instrument for measuring the inherent optical absorption and attenuation properties of seawater and its constituents *in situ* (Wetlabs 2001; Twardowski 2001). The AC-9 was extensively calibrated at sea using twice-daily following (Twardowski *et al.* 1999) and corrected for scattering on the absorption measurement (Wetlabs 2001; Zaneveld *et al.* 1994). Interpolated estimates of the IOPs were generated for SPMR wavelengths using cubic spline interpolation with a tension of 1.0, implemented under the Interactive Data Language (IDL: Research System Inc., USA).

In situ backscattering measurements

A Wetlabs three-angle, three-wavelength volume scattering function meter (ECO-VSF3) was used to measure backscattering at 450, 530 and 650 nm. The data were processed as Wetlabs (2004), assuming a volume scattering function that approximates to that given by Petzold (1972). The instrument response was found to “saturate” when total suspended particulate matter concentration exceeded $\sim 10 \text{ g m}^{-3}$, and these saturated data were not used in the subsequent analysis.

Bootstrap analysis

Studentised bootstrap analysis was used to test the agreement between two sets of paired data (Efron and Tibshirani 1993) by computing confidence intervals for ratios of properties estimated by the remote-sensing algorithm, and in situ measurements of those properties. A confidence interval that does not include unity suggests the difference is statistically significant at the 95% confidence level.

Results

Vertical structure

In many cases, especially near the coast, the water column was not well mixed vertically. There was typically a thin layer of fresher water overlying denser, more saline water. Bio-optical properties in the surface layer were very different to those deeper in the water column. For example, beam attenuation was often considerably higher (by a factor of >3) in the surface, fresher water layer than deeper in the water column. We determined an “optical mixed layer depth”, OMLD, for each station, over which the bio-optical properties of the water column are considered to significantly affect the colour of the water as sensed by an above-surface observer, and which will be retrieved through ocean colour satellite remote sensing. All point-depth, biogeochemical measurements based on water-samples collected by Nisquin bottle refer to average values over this OMLD. Data from profiling equipment, where we have measurements at a number of different depths, were combined by optically weighting data using a modified version of the scheme given by Gordon and Clark (1980).

Biogeochemical properties

Two key near-surface biogeochemical properties are given in Figure 6. Chlorophyll-a concentrations varied between 0.4 and 1.7 mg m^{-3} for the stations visited in this study. These are moderate-low concentrations for coastal waters. Lower Ca values tended to be found inshore, whereas higher values tended to occur further offshore. SPM concentrations varied

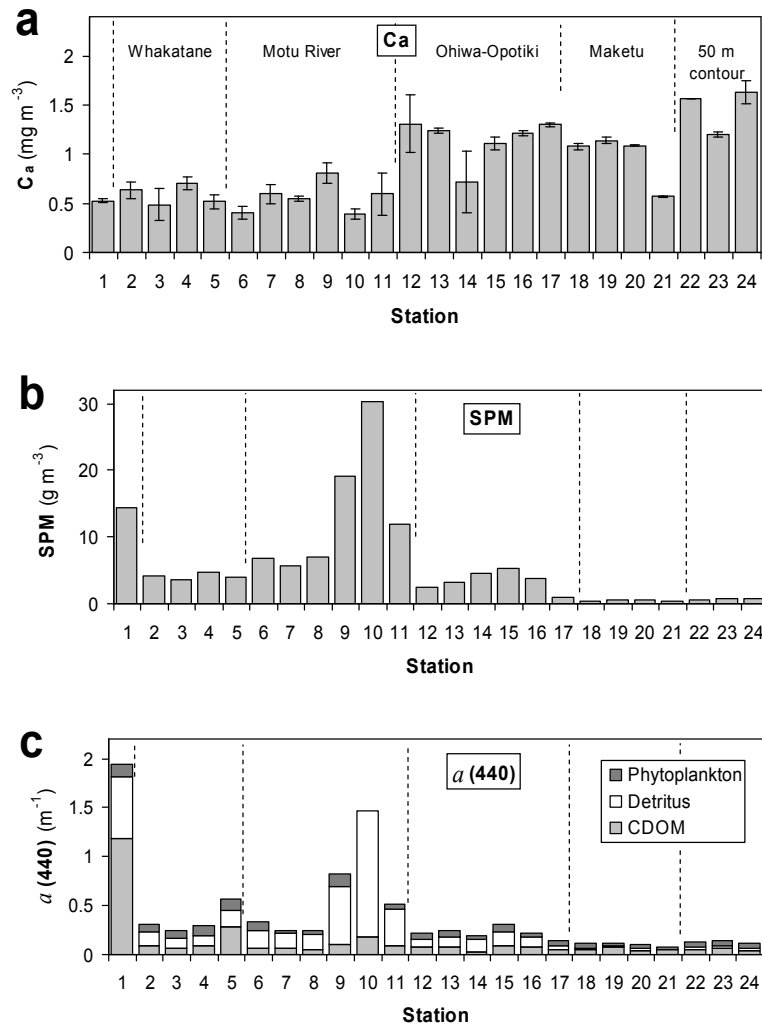


Figure 6: Summary of biogeochemical properties. (a): Chlorophyll-a concentration, C_a (b): Total suspended particulate matter concentration (SPM); (c): Absorption at 440 nm

between 0.2 g m^{-3} and $>30 \text{ g m}^{-3}$, with higher values near the mouths of rivers (especially the Whakatane and Motu rivers), and lower values offshore. This variation of SPM of more than an order of magnitude represents an excellent dataset with which to regionalise a remote sensing algorithm. All stations were classified as being Case 2 on the basis of having high $R_{rs}(510)$ values. Most stations were also classified as Case 2 on the basis of their SPM concentrations (all but 18 and 21), and most on the basis of their CDOM absorptions (all but 14 and 20).

Apparent Optical Properties

Remote sensing reflectance varied between 0.003 and 0.19 sr^{-1} across the visible spectrum (Figure 7a). Reflectance tended to be considerably higher than found in oceanic (Case 1) waters. Diffuse attenuation at 490 nm varied between 0.07 and 5.3 m^{-1} , giving attenuation depths of between 0.2 and 13.4 m (Figure 7b). As mentioned previously, attenuation was often not constant with depth near the surface as the amount of coloured material in the water was not well mixed vertically. In these cases, it was necessary to use a depth-dependent attenuation coefficient to calculate optical weightings for material in the water.

Absorption

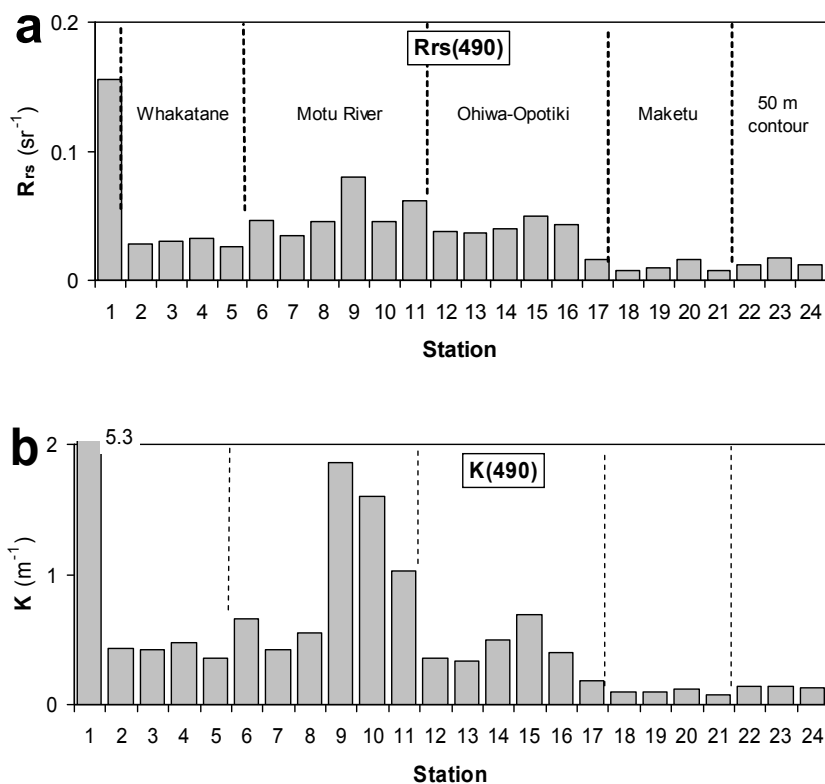


Figure 7: Summary of Apparent Optical Properties. (a) Remote sensing reflectance at 490 nm, $R_{rs}(490)$; (b) Near-surface diffuse attenuation coefficient at 490 nm, $K(490)$

Total optical absorption can be divided into that due to water itself (a_w), coloured dissolved organic matter (CDOM; a_g), particulate detritus (a_d), and living phytoplankton cells (a_{ph}). Water dominates absorption at wavelengths >600 nm, but water absorption is small for wavelengths between 410 and 500 nm.

Absorption by CDOM measured by the spectrophotometric method closely followed work by Bricaud *et al.* (1981), with S being between 0.013 and 0.023 nm^{-1} (mean 0.016 nm^{-1}). These values are very similar to previous measurements in many other coastal regions around the world (Howard-Williams *et al.* 1995; Kirk 1994).

It is generally taken that absorption by particulate detritus (a_d) is minor compared to that of other material in the water, generally making up <20% of total absorption across all visible wavelengths. This was not the case here. Absorption by particulate detritus (a_d), as determined by the bleached filter paper method, was often considerable across the visible spectrum, varying between 10 and 85% of the total absorption (average ~40%). Absorption due to particulate detritus varied exponentially with wavelength, with the index S between -0.009 and -0.014 nm^{-1} (mean: -0.011 nm^{-1}). The absorption spectra of the dissolved and particulate detritus were distinct, though differences were small.

Figure 8 shows the ratio of $\epsilon = a(490)/a(510)$ by station. The IOP algorithm relies on this ratio being known in advance. The ratio measured in the Bay of Plenty varied between 1.22 and 1.42 (mean value of 1.32) and it is significant that the values of ϵ are slightly less than the range found in Europe (Moore and Aiken 2004) and used by the IOP algorithm of 1.32–1.58. The measured ϵ lay within this range at only 8 of the 24 stations, and at the other stations, $\epsilon < 1.32$. The low values of ϵ in the Bay of Plenty region may result in part from the unusually high amounts of absorption due to particulate detrital material. The IOP algorithm relies on

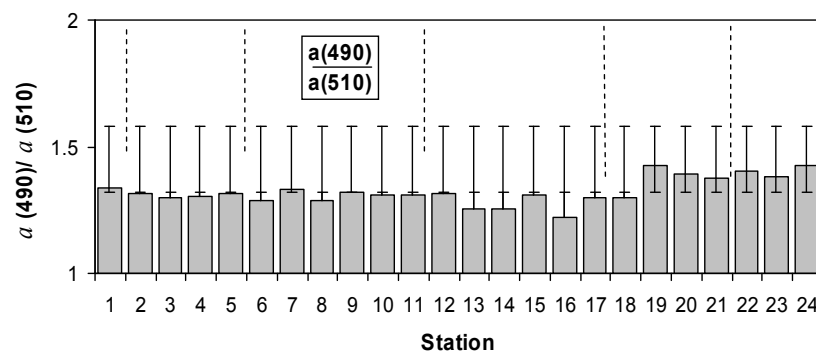


Figure 8: The ratio of $a(490)/a(510)$ by station. The error bars show the range of values found in Europe by Moore and Aiken (2004).

the consistency of ϵ between different bio-optical provinces, suggesting that the first part of the IOP algorithm may need to be modified to perform effectively in the Bay of Plenty region.

Scattering and back-scattering

Scattering was calculated from the AC-9 by differencing attenuation and absorption. Scattering due to material in the water was always much greater than scattering by water itself, being responsible for over 99% of total scattering at all wavelengths. The spectral variations of b are shown in Figure 9a. The linear function of Moore and Aiken (2004) describes the Bay of Plenty AC-9 scattering measurements relatively well (within 10%) through the whole visible spectrum. It is unlikely that the small differences between our measured values of b and those used by the model will affect the performance of the IOP algorithm. However, the IOP algorithm will be highly sensitive to how well it predicts the spectral shape of the backscattering coefficient (b_b), as this is used to extrapolate scattering estimates at 490 nm to other wavelengths. Errors in estimating the spectral shape of b_b by the

algorithm will translate directly to errors in the estimated values of a at 412, 443, 555 and

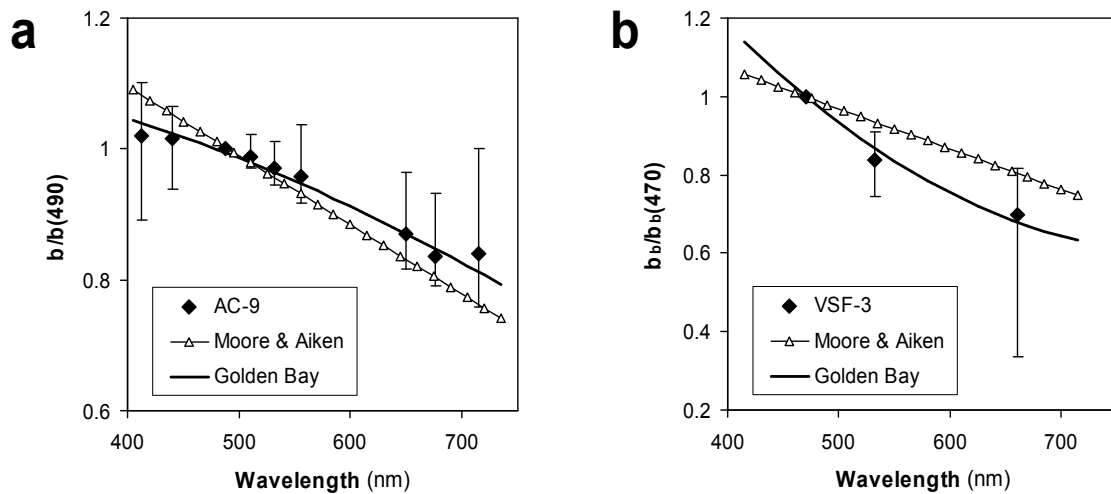


Figure 9: Spectral variations in scattering. a: Total scattering, referenced to 490 nm, $b/b(490)$, measured by the AC-9. b: Backscattering referenced to 470 nm $b_b/b_b(470)$ measured by the VSF-3. The symbols and error bars show the range of values measured in the Bay of Plenty. The spectral variation used by the IOP algorithm (Moore and Aiken 2004), and that found in Golden Bay are also shown

665 nm. Backscatter in natural Case 2 waters is difficult to measure and there have been few reliable published measurements of the spectral variation in b_b . Given that the variability in $\tilde{b} = b_b / b$ is poorly known, it is often assumed that \tilde{b} is invariant with wavelength and has the same value everywhere (e.g., Moore and Aiken 2004). The average value of San Diego Harbour measurements (0.01756: Petzold 1972; Haltrin and Mankovsky 2002) is used to describe \tilde{b} in the IOP algorithm described by Moore and Aiken (2004). The assumption that \tilde{b} is independent of wavelength is not supported by measurements in the Bay of Plenty. Our data (Figure 9b) indicate that \tilde{b} decreased by $\sim 30\%$ between 440 and 665 nm, and that the spectral shape in the Bay of Plenty is similar to that found in Golden Bay, Tasman Bay and the Marlborough Sounds (Pinkerton et al. 2004a).

Inherent Optical Property Algorithm Modifications

Several modifications to the IOP algorithm were made for the Bay of Plenty from the IOP algorithm published by Moore and Aiken (2004), including:

- $a(490)/a(510)$ is allowed to vary between 1.32 and 1.45.
- the spectral shape of b_b is modified in line with the results from the Bay of Plenty and Golden Bay/Tasman Bay/Marlborough Sound work.
- Chlorophyll-a concentration is estimated from absorption at 490 nm, corrected for absorption by suspended sediment at this wavelength.

Performance of the Inherent Optical Algorithm

After the modifications described above, the Inherent Optical Property algorithm was effective at estimating spectral absorption and backscattering at 490 nm from measurements

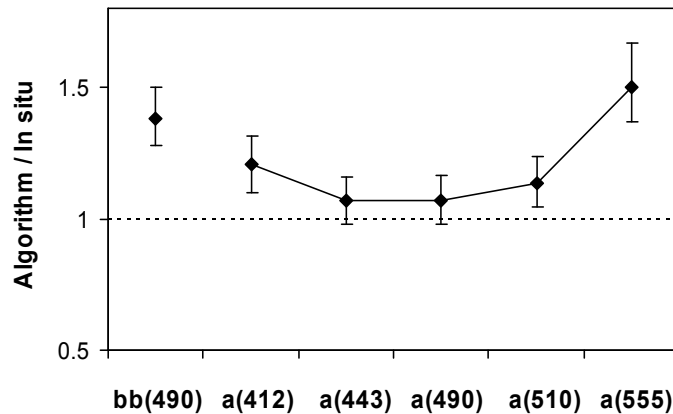


Figure 10 Retrieval of Inherent Optical Properties of the Bay of Plenty from ocean colour measurements. Bootstrap analysis of data

of ocean colour (Figure 10). Test statistics were calculated as the ratio of the estimated value of the IOP to the value measured in situ. Bootstrap analysis (Efron and Tibshirani 1993; Venables and Ripley 1999) indicated that the deviation of this ratio from unity was not statistically-significant at the 95% confidence level for absorption at 443 nm and 490 nm. The over-estimation of backscatter by the algorithm by 35% was statistically significant. These three IOPs alone ($b_b(490)$, $a(443)$, and $a(490)$) are used by the algorithm to estimate SPM, CDOM and chlorophyll-a concentration.

Characterisation of Suspended Sediment Optical Properties

Work in coastal waters (e.g. Bale et al. 1994; Babin et al. 2000) shows that for a given sediment type, there is generally a good relationship between scattering (or backscattering) and SPM concentration, but that this relationship is dependent on the particle size distribution, particle shape, and chemical composition of the sediment, and is consequently less robust if different sediment types are considered together. The optical properties of phytoplankton and CDOM tend to be less regionally variable than those of suspended particulate matter (Bricaud et al. 1995; Bricaud and Prieur 1981). For this reason, the fieldwork conducted in the Bay of Plenty focused on characterising the optical properties of sediment. Results measured by the AC-9 and VSF-3 in the Bay of Plenty allowed us to estimate SPM concentration from $b_b(490)$

(Figure 11). Eqn (1) was used to capture the reduction in sediment-specific backscattering for concentrations $>10 \text{ g m}^{-3}$.

$$SPM = \exp(B_0 + B_1\chi + B_2\chi^2) + B_3 \quad \text{where } \chi = \ln b_b(490) \quad (1)$$

As mentioned previously, sediment in the Bay of Plenty was found to absorb significantly across the visible spectrum. The absorption at 490 nm due to sediment (a_d) was linearly related to SPM concentration, except at low concentrations ($SPM < 3 \text{ g m}^{-3}$). Linear least

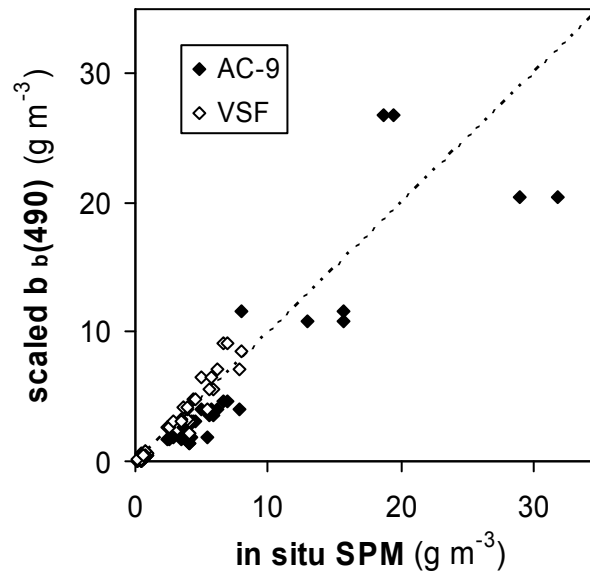


Figure 11: Retrieval of Suspended Particulate Material concentration (SPM) from backscattering at 490 nm, $b_b(490)$ using eqn 1. The dashed line shows 1:1 correspondence.

squares, with a low-SPM correction, estimated $a_d(490)$ with an average difference of 22% ($N=48$, $R^2=0.97$, Figure 12). This absorption is used to correct total estimated absorption at 490 nm for the effects of sediment.

Estimation of Chlorophyll-a concentration

Chlorophyll-a concentration was estimated from absorption at 490 nm, corrected for absorption by suspended sediment at this wavelength. Separating absorption at 490 nm into that due to CDOM and that due to phytoplankton was not found to reduce the uncertainty with which chlorophyll-a concentration could be estimated. Chlorophyll-a concentrations in the Bay of Plenty during the fieldwork were low ($<2 \text{ mg m}^{-3}$), and were present against a background of high sediment concentration which was highly absorbing. At 490 nm, the average proportion of absorption due to chlorophyll was only 30%, with a range of 2–58%. At stations where SPM is high, chlorophyll is typically responsible for less than 8% of the total absorption. Under these conditions, small errors in measuring total absorption, combined with small errors in estimating absorption due to SPM lead to large errors in estimating chlorophyll-a concentration. Estimating CDOM absorption, to produce an estimate of

absorption due to phytoplankton alone, exacerbated these problems. Bootstrap analysis was used to estimate whether chlorophyll concentrations estimated from ocean colour

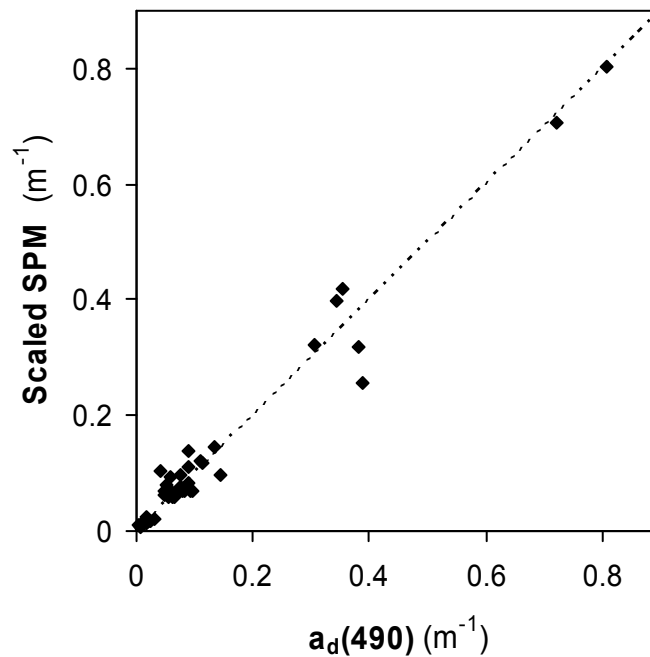


Figure 12 Estimation of detrital absorption at 490 nm using SPM concentration. The dashed line shows 1:1 correspondence

measurements are likely to be biased relative in situ values (Figure 13). The same analysis was applied to estimates of chlorophyll-a concentration produced by the standard open-ocean NASA OC4v4 algorithm.

Chlorophyll-a concentration by the NASA Case 1 (open-ocean) algorithm overestimates the value of chlorophyll-a measured in situ by a factor of about 2.3. Chlorophyll-a concentration values estimated by the modified Case 2 Bay of Plenty algorithm do not differ from the in situ values at the 95% confidence level. There is considerable scatter in the agreement in both cases (wide 95% confidence intervals), suggesting that there is considerable variability in the bio-optical properties of the water constituents not considered by the algorithm. Further fieldwork is required to reduce this confidence interval.

Conclusions

It was suggested that one of the major advantages of using an IOP algorithm to estimate biogeochemical properties of the water column from remote measurements of ocean colour is that only the second part of the algorithm generally needs to be modified according to region; the initial conversion from R_{rs} values to IOP values is expected to be much less variable in space and time (Moore and Aiken 2004). The results presented here support this assertion.

The remote sensing IOP algorithm of Moore and Aiken (2004), with some regional modifications as described was shown to work well in estimating $b_b(490)$ and absorption between 412 and 555 nm from measurements of R_{rs} . The algorithm estimated the critical absorption values of $a(443)$ and $a(490)$ with no statistically significant bias at the 95% confidence level. Backscatter was overestimated by 35% which will tend to lead to suspended

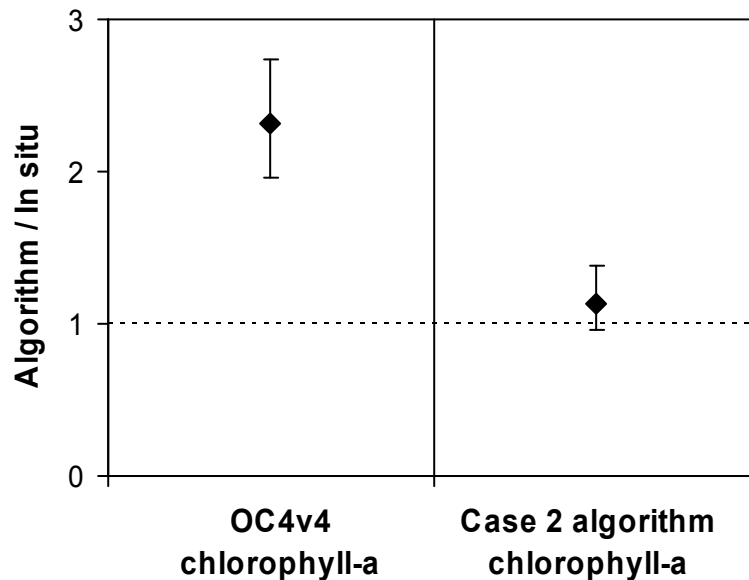


Figure 13 Bootstrap analysis of the estimation of chlorophyll-a concentration using the NASA open-ocean algorithm (OC4v4) and the Bay of Plenty Case 2 algorithm

sediment being overestimated by the algorithm.

We found significant differences between the bio-optical properties of the Bay of Plenty, and between other coastal regions of New Zealand (Golden Bay, Tasman Bay, Marlborough Sounds), and between the default values IOP algorithm which represent “European average” bio-optical conditions. The fieldwork has allowed us to “regionalise” the second stage of the IOP Case 2 algorithm to the Bay of Plenty so that region-specific algorithm can be applied to the archived SeaWiFS measurements of ocean colour held at NIWA to generate a spatial and temporal database of chlorophyll-a concentration, total suspended particulate matter, total detrital absorption and dissolved detrital absorption.

Future Work

To test the quality and internal consistency of the inherent and apparent optical properties for the Bay of Plenty region, optical closure (Pinkerton et al. 2004a; Pegau and Zaneveld 1995) is required. Further work to test and improve the quality of the measurements of absorption in the Bay of Plenty are possible, but will require additional analysis time.

The development of the Bay of Plenty region algorithm was based on data collected for one period of a seasonal year, June 2004. Performance of the algorithm for other seasonal periods,

such as spring - when phytoplankton dominate the optical properties of the water column is not known. The variability of bio-optical properties in coastal marine environments is a focus of remote sensing work in many parts of the world. To understand the significance of this variability for remote sensing of New Zealand coastal regions requires repeated monitoring. Additional fieldwork in the Bay of Plenty in the spring would be a valuable extension to this work.

Finally, simultaneous measurements of bulk water reflectance through the red and near infrared part of the spectrum (600–880 nm) with total suspended particulate material concentration would be extremely useful to allow the Case 2 atmospheric correction method to be tested in the Bay of Plenty region. These measurements would require either laboratory or field-based experiments using an above-surface spectroradiometer. A field procedure for this work is presently under development at NIWA.

Acknowledgments

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Table 1: Acronyms and symbols used in this work

Symbol	Definition	Units
IOP	Inherent Optical Property	...
HPLC	High Performance Liquid Chromatography for phytoplankton pigment concentrations	...
CDOM	Coloured Dissolved Organic Matter; measured as $a_g(440)$...
SPM	Suspended Particulate Material (concentration)	g m^{-3}
C_a	Chlorophyll-a concentration	mg m^{-3}
a	Absorption coefficient of water constituents	m^{-1}
a_t	Total absorption coefficient	m^{-1}
a_w	Absorption coefficient of water	m^{-1}
a_{ph}	Absorption coefficient of phytoplankton	m^{-1}
a_d	Absorption coefficient of particulate detritus	m^{-1}
a_g	Absorption coefficient of CDOM	m^{-1}
a_{ph}^*	Chlorophyll-specific phytoplankton absorption	$\text{m}^2 \text{mgChl}^{-1}$
b	Scattering coefficient of particulate material	m^{-1}
b_w	Scattering coefficient of water	m^{-1}
b_p	Scattering coefficient of	m^{-1}
b_{bt}	Total backscattering coefficient	m^{-1}
$\tilde{b} = b_b/b$	Backscatter to total scattering ratio of particulates	...
$\beta(\theta)$	Volume scattering function	$\text{m}^{-1} \text{sr}^{-1}$
c	Attenuation coefficient	m^{-1}
λ	Wavelength	nm
R_{rs}	Remote sensing reflectance	sr^{-1}
θ	Sensor view angle	°
θ_0	Solar zenith angle	°
$\Delta\phi$	Sun-sensor azimuth difference	°

Table 2: Station positions for EBoP0604

Date	ID	Location	File	Lat °S	Lon °W	Depth M	Cloud /8	Wind kts
6/06/2004	1	Whatane estuary	2004060601	37.951	177.000	3	0	15
7/06/2004	2	Whakatane	2004060701	37.932	177.000	12	0	3
7/06/2004	3	Rangitaiki River	2004060702	37.903	176.891	12	0	3
7/06/2004	4	Rangitaiki River	2004060703	37.903	176.881	9	1	4
7/06/2004	5	Whakatane	2004060704	37.928	177.004	16	1	4
8/06/2004	6	Offshore Motu River	2004060801	37.844	177.514	25	0	10
8/06/2004	7	Offshore Motu River	2004060802	37.853	177.541	17	0	11
8/06/2004	8	Offshore Motu River	2004060803	37.863	177.568	13	0	12
8/06/2004	9	Offshore Motu River	2004060804	37.863	177.578	7	0	9
8/06/2004	10	Motu River mouth 1	2004060805	37.850	177.583	4	0	8
8/06/2004	11	Motu River mouth 2	2004060806	37.844	177.579	5	0	8
9/06/2004	12	Ohiwa	2004060901	37.843	177.580	9	0	1
9/06/2004	13	Waioeka River	2004060902	37.984	177.267	4	0	1
9/06/2004	14	Opotiki	2004060903	37.977	177.369	6	0	3
9/06/2004	15	Waiawa River mouth	2004060904	37.978	177.391	9	0	4
9/06/2004	16	Pehitari Point	2004060905	37.943	177.478	10	0	4
9/06/2004	17	Offshore of Opotiki	2004060906	37.910	177.277	36	0	8
10/06/2004	18	Matata	2004061001	37.793	176.740	30	0	5
10/06/2004	19	Otamarakau	2004061002	37.716	176.550	29	0	5
10/06/2004	20	Okurei Point	2004061003	37.680	176.439	30	0	2
10/06/2004	21	Motuhaku Island	2004061004	37.626	176.528	80	0	3
11/06/2004	22	Offshore of Ohiwa	2004061101	37.879	177.092	50	8	3
11/06/2004	23	50 m contour west	2004061102	37.863	177.192	50	7	3
11/06/2004	24	50 m contour east	2004061103	37.857	177.323	50	7	1

Table 3: Vertical water structure for EBoP0604

Station	Depth	Description	Surface	Deep	OMLD ⁷
ID	m		salinity	salinity	m
1	3	Well mixed vertically	1.3	As shallow	5.0
2	12	Gradual mixing with depth	32.9	35.0	2.0
3	12	Three layers: fresher/mixing/mixed	30.7	35.1	1.5
4	9	Gradual mixing with depth	33.8	35.1	1.5
5	16	Three layers: fresher/mixing/mixed	4.2	35.0	3.2
6	25	Three layers: fresher/mixing/mixed	3.0	35.2	3.5
7	17	Three layers: fresher/mixing/mixed	32.4	35.2	4.0
8	13	Three layers: fresher/mixing/mixed	24.8	35.2	2.0
9	7	Three layers: fresher/mixing/mixed	23.4	35.1	1.2
10	4	Three layers: fresher/mixing/mixed	11.7	35.1	1.2
11	5	Three layers: fresher/mixing/mixed	22.4	35.1	1.2
12	9	Well mixed below 0.6 m	35.0	As shallow	1.2
13	4	Gradual mixing with depth	30.8	35.0	1.2
14	6	Three layers: fresher/mixing/mixed	34.5	34.9	1.5
15	9	Gradual mixing with depth	34.5	34.8	1.2
16	10	Gradual mixing with depth	34.5	35.0	3.5
17	36	Thermally stratified	35.2	As shallow	0.5
18	30	Thermally stratified to 25 m	35.1	As shallow	0.5
19	29	Thermally stratified	35.1	As shallow	0.7
20	30	Thermally stratified	35.1	As shallow	0.5
21	80	Thermally stratified	35.1	As shallow	0.7
22	50	Thermally stratified	35.2	As shallow	0.7
23	50	Thermally stratified	35.1	As shallow	0.7
24	50	Thermally stratified	35.2	As shallow	0.7

⁷ OMLD: Optical mixed layer depth