

Regional variations in bio-optical properties of the surface waters in the Southern Ocean

NICOLA FENTON^{1,2}, JULIAN PRIDDLE³ and PAUL TETT¹

¹*School of Ocean Sciences, University of Wales Bangor, Menai Bridge, Anglesey LL59 5EH, UK*

²*Present address: Scott Polar Research Institute, University of Cambridge, Lensfield Road, Cambridge CB2 1ER, UK*

³*British Antarctic Survey, Natural Environment Research Council, High Cross, Madingley Road, Cambridge CB3 0ET, UK*

Abstract: Values of attenuation coefficient, $K_d(\lambda)$, for five visible wavelengths are reported for 14 sites around South Georgia and the Bransfield Strait, in the Southern Ocean. The mean chlorophyll-plus-phaeopigment concentrations in the upper 30 m of the water column ranged from 0.32–6.633 mg m⁻³ with one particularly high mean value of 31 mg m⁻³. Partition of attenuation between chlorophyll (K_c) and other factors in the water column (K_o) indicated that the spectral character of K_o in the Bransfield Strait was consistent with absorption by non chlorophyll-like pigments (Gelbstoff). Values were significantly different between the two areas. Values of the specific attenuation coefficient due to pigment concentration (K_p) were small compared to temperate values. These data support other studies in suggesting that the application of remotely sensed ocean colour data to global biogeochemical surveys requires the development of regional algorithms.

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Introduction

As light penetrates the water column its spectral and energy characteristics are modified by dissolved and suspended substances. It has become increasingly important to classify optical water types and define optical properties. Jerlov (1968) originally used attenuation coefficients to characterize different water bodies into five optical water types. Smith & Baker (1978 a) introduced the concept of bio-optical state to relate the “total effect of biological processes on the optical properties of natural waters”.

The attenuation of light with depth in a water column is of biological importance since phytoplankton need light energy to photosynthesize. The extent to which light is attenuated and the resulting spectral composition are factors which determine phytoplankton production and distribution in the Southern Ocean. This is an important region with respect to global carbon flux since large concentrations of nutrients in the surface waters (Hayes *et al.* 1984, Nelson & Gordon 1985, Priddle *et al.* 1993) indicate the potential for increased primary production, which could be significant in the drawdown of anthropogenic atmospheric carbon dioxide (Taylor 1992).

The Southern Ocean is a poorly sampled region with respect to optical properties and yet parameterization of these properties will be of value when Sea-Viewing Wide Field of View Sensor (SeaWiFS) is launched. The problem of spatial heterogeneity in optical properties of phytoplankton is a crucial one for the study of the global role of the oceans, if reasonably accurate estimates of biomass or productivity are to be obtained. This has been addressed by the definition of biogeochemical provinces, areas of the ocean in which the properties of the phytoplankton are consistent and can be predicted from a restricted suite of measurements (Platt *et al.* 1991). This paper reports optical

measurements from two areas of the Southern Ocean and shows that on the basis of these measurements the two areas can be regarded as distinct biogeochemical provinces.

Methods

The British Antarctic Survey ship RRS *John Biscoe* surveyed two distinct areas, the Bransfield Strait and the waters around South Georgia, from December 1987 to February 1988. Water samples were collected over a range of depths from the surface to 30 m using 2.5 dm³ Niskin bottles on a rosette attached to a Neil Brown CTD. Sub-samples (0.25 dm³) were filtered through Whatman GF/F filters, which were then placed in 10 cm³ of 90% acetone for 24 h at -2°C in the dark. After this time fluorescence before and after acidification was determined using a filter fluorometer (Turner Designs Model 112), calibrated using pure chlorophyll *a* (Sigma Chemical Company). For every station, chlorophyll and phaeopigment concentrations, at each depth measured, were summed to determine overall pigment concentration.

Downwelling irradiance was measured using the University College of North Wales (School of Ocean Sciences) irradiance meter (Mitchelson *et al.* 1988). This consists of an underwater and a surface unit. The underwater unit has five channels centred on wavelengths, 444, 521, 552, 596 and 670 nm, each having a bandwidth of 12 nm, except 444 nm which has a bandwidth of 10 nm. These wavelengths correspond to the Coastal Zone Colour Scanner (CZCS) wavelengths. The surface unit is a broad band irradiance detector (400–700 nm). The ratio of single waveband irradiance at depth to broadband irradiance at the surface (I_z/I_0) was calculated for each wavelength at each depth measured. The natural log of I_z/I_0 was regressed

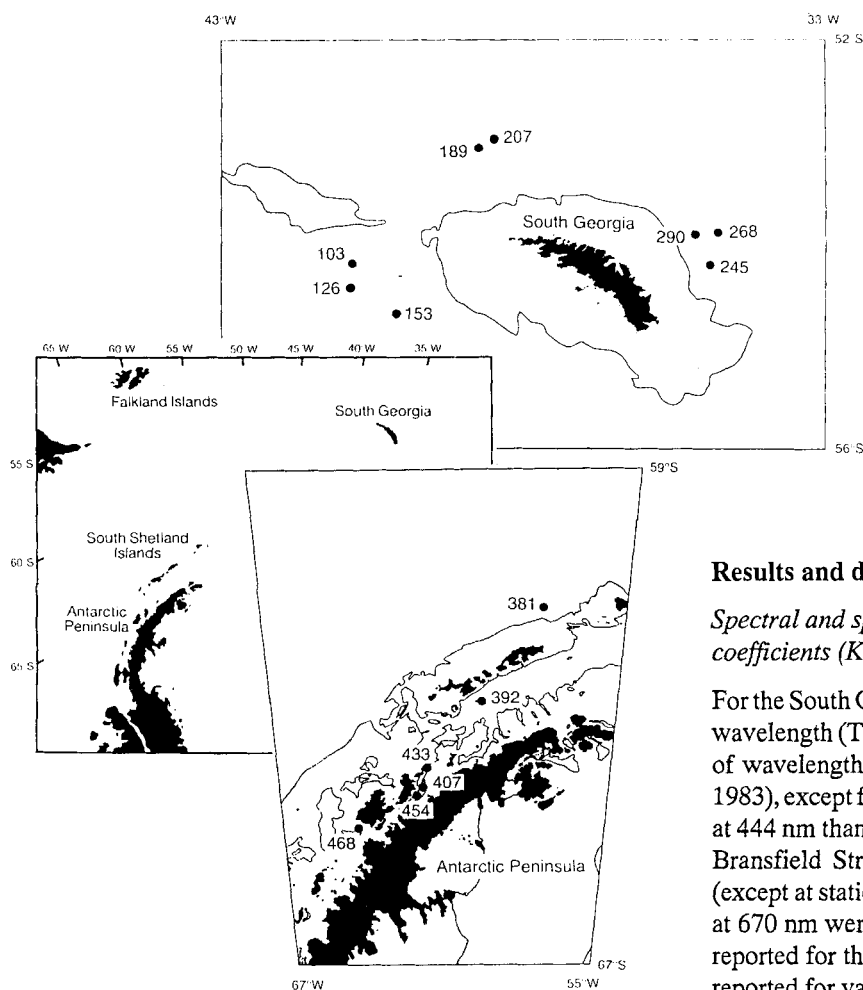


Fig. 1. A map showing the two areas studied. The numbers correspond to the stations at which optical and pigment data were collected. Contour line is at 500 m.

against depth to obtain the diffuse attenuation coefficient for that wavelength ($K_d(\lambda)$).

Study sites

Studies were undertaken in two contrasting areas of the Southern Ocean. The first was carried out in the waters adjacent to South Georgia (Fig. 1), an oceanic island situated within the Antarctic Circumpolar Current (ACC). The water masses which surround the island consist of ACC water mixed with varying amounts of subantarctic water (Priddle *et al.* 1986). The limited data available for this area suggest that high phytoplankton biomass occurs, although it is very patchy (Priddle *et al.* 1986, Whitehouse *et al.* 1993).

The second study was carried out within the Bransfield Strait (Fig. 1), including the Gerlache Strait. The Bransfield Strait itself consists of two interlinked basins bounded by the Antarctic Peninsula on one side and the South Shetland Islands on the other. The hydrography of this area is complex with different water masses being formed by the mixing of Bellingshausen Sea surface water and Weddell Sea surface water (Heywood 1985). The Gerlache Strait is continuous with the Bransfield Strait and is a well-sheltered stretch of water. Values of phytoplankton biomass as high as 50 mg m^{-3} have been recorded for this area (Heywood & Priddle 1987, Mitchell & Holm-Hansen 1991).

Results and discussion

Spectral and spatial variability of diffuse attenuation coefficients ($K_d(\lambda)$)

For the South Georgia data, the variation in ($K_d(\lambda)$) values with wavelength (Table I) was consistent with the standard patterns of wavelength dependent absorption of light by water (Kirk 1983), except for stations 189 and 207 which had higher values at 444 nm than at 521 nm. Values of $K_d(\lambda)$ were higher in the Bransfield Strait than in the waters around South Georgia (except at stations 189 and 207). In both areas values of $K_d(\lambda)$ at 670 nm were highly variable. Values are within the range reported for the Southern Ocean and are comparable to those reported for various other areas (Table II).

In the Bransfield Strait, and at stations 189 and 207 around South Georgia, values of K_d at 444 nm were as high as those at 521 nm and in some cases higher. This indicates that there was a greater concentration of an attenuating substance present in these particular water columns which attenuated greatest at low wavelengths. From Table III it can be seen that in the waters of the Bransfield Strait and at stations 189 and 207 around South Georgia there were relatively high concentrations of chlorophyll *a* pigment in the water column. Chlorophyll *a* pigments absorb strongly at 444 nm and could possibly have been the cause of the high attenuation coefficient at this wavelength.

The attenuation coefficient for a particular water column, $K_d(\lambda)$, can be partitioned between attenuation due to the variable phytoplankton biomass (chlorophyll pigments), and the supposedly constant properties of water and other substances. The linear relationship between $K_d(\lambda)$ and its constituents may be summarized by -

$$K_d(\lambda) = K_0 + (K_c \cdot C) \quad (1)$$

where K_0 = attenuation due to water, and non chlorophyll-like substances (m^{-1})

K_c = attenuation coefficient per unit pigment concentration ($\text{m}^2 (\text{mg chl})^{-1}$).

C = concentration of pigment (mg m^{-3})

Table I. Values of attenuation coefficients, K_d (m^{-1}) from South Georgia and the Bransfield Strait. Antarctic summer 1987–88.

Station	K_d (444)	r^2	K_d (521)	r^2	K_d (552)	r^2	K_d (596)	r^2	K_d (670)	r^2
South Georgia										
103	0.0574	0.99	0.0756	0.99	0.0961	0.99	0.1340	0.97	0.3030	0.82
126	0.0563	0.99	0.0702	0.99	0.0882	0.99	0.1290	0.98	0.6420	0.67
153	0.0588	0.99	0.0734	0.99	0.0891	0.99	0.1260	0.98	0.5430	0.80
189	0.1100	0.96	0.0916	0.96	0.1310	0.97	0.1880	0.96	0.4510	0.94
207	0.1240	0.98	0.1050	0.98	0.1140	0.98	0.1380	0.96	0.1660	0.97
245	0.0530	0.98	0.0701	0.98	0.0746	0.98	0.1130	0.97	0.4870	0.86
268	0.0682	0.99	0.0760	0.99	0.0941	0.99	0.1430	0.99	0.4100	0.85
290	0.0678	0.99	0.0740	0.99	0.0897	0.99	0.1480	0.98	0.3730	0.92
Bransfield Strait										
381	0.1170	0.97	0.1230	0.87	0.1510	0.93	0.1900	0.95	0.4300	0.93
392	0.1080	0.98	0.0881	0.98	0.1890	0.99	0.1700	0.98	0.4390	0.88
407	0.3030	0.94	0.3730	0.99	0.3130	0.99	0.3850	0.99	0.6590	0.66
433	0.0883	0.99	0.0869	0.97	0.0985	0.99	0.1500	0.96	0.3460	0.92
454	0.1330	0.99	0.1020	0.99	0.1300	0.99	0.1660	0.99	0.3510	0.89
468	0.1410	0.95	0.1190	0.89	0.1240	0.97	0.1830	0.96	0.3430	0.95

Regression of $K_d(\lambda)$ on pigment concentration yields values for K_c and K_0 (slope and intercept respectively, Table IV and Fig. 2) For South Georgia, the regressions showed strong correlations (r^2 for all λ except 670 nm 0.39–0.83, Table IV). The observations from the Bransfield Strait also showed a high correlation (r^2 for all wavelengths except 670 nm 0.82–0.97, Table IV), but the regression is driven by one very high chlorophyll concentration at station 407. Excluding the outlier reduced the correlation markedly (r^2 0.0–0.382). However, on this local scale we have no *a priori* reason to reject this data point, although it clearly plays a major role in determining the optical properties of the Bransfield Strait. The values of K_0 yielded by the regressions for the two regions were significantly different at wavebands 444 nm, 552 nm, and 596 nm (Table V) suggesting different optical properties of the water column in the two regions. Values of K_c were only significantly different at 444 nm (Table V) suggesting that the optical properties of the phytoplankton were similar in the two regions.

Attenuation due to pigments

Values of K_c shown in Table IV are lower than published values from a range of geographical areas (Table II). Mitchell (1992) also found values of K_c in the Southern Ocean to be lower than in temperate waters, although our values are lower than his. Mitchell (1992) put forward a hypothesis that several factors were interacting concurrently to give low values of K_c in the Southern Ocean. Important factors may include algal type, water colour and depth (Atlas & Bannister 1980), cellular architecture and pigment composition (Platt & Jassby 1976) and irradiance (Falkowski *et al.* 1985).

In the South Georgia area the variation of K_c with wavelength was consistent with chlorophyll *a* absorption at different wavelengths (Kirk 1983). In the Bransfield Strait the variation of K_c with wavelength did not show that of the classic chlorophyll *a* absorption spectra, but showed a small maximum at 521 nm.

Table II. Values of attenuation coefficient, K_d (m^{-1}), attenuation per unit pigment, K_c (m^2 (mg chl) $^{-1}$) and attenuation due to water and non chlorophyll-like substances, K_0 (m^{-1}) from the literature.

Wavelength (nm)	K_d	K_c	K_0	Author/area
444	0.025–0.6	0.038	0.023	Smith & Baker (1978b)
521	0.05–0.375	0.019	0.048	Various areas
552	0.07–0.3	0.012	0.063	
596	0.1–0.3	0.007	0.121	
670	-	0.015	0.460	
425	0.049–0.3	-	-	Stramski & Montwill (1982)
465	0.04–0.248	-	-	South Shetland Is. and Drake Passage
525	0.07–0.175	-	-	
535	0.069–0.172	-	-	
580	0.131–0.215	-	-	
620	0.25–0.481	-	-	
680	0.568–0.757	-	-	
441	-	0.149	0.0207	Siegal & Dickey (1987)
520	-	0.047	0.0479	North Pacific Ocean
560	-	0.019	0.0758	
589	-	0.0	0.1344	
671	-	0.0	0.4708	
488	1	-	-	Holm-Hansen & Mitchell (1991)
488	0.06	-	-	Near Gerlache Strait, bloom. Drake Passage, non-bloom
441	-	0.025	0.054	Mitchell (1992). Antarctic Peninsula and adjacent waters of Drake Passage and Bellingshausen Sea
520	-	0.015	0.059	
560	-	0.009	0.066	
683	-	0.013	0.480	

The phytoplankton at both South Georgia and Bransfield Strait were found to be dominated by large diatoms, and there was no gross taxonomic difference between the two areas which could account for the variation in values of K_c . Given the small sample size and the marked statistical effect of the data from station 407, it would be inappropriate to speculate further on the K_c spectra from the Bransfield Strait.

Table III. Mean pigment concentrations to 30 m, from South Georgia and the Bransfield Strait. Antarctic summer 1987–88.

Station	Chlorophyll (mg m ⁻³)	Phaeopigment (mg m ⁻³)	Total (mg m ⁻³)
South Georgia			
103	0.39	0.123	0.513
126	0.346	0.07	0.416
153	0.233	0.083	0.316
189	6.453	0.18	6.633
207	4.463	0.736	5.199
245	0.933	0.176	1.109
268	0.266	0.07	0.336
290	0.413	0.173	0.586
Bransfield Strait			
381	2.647	0.387	3.034
392	1.9	0.416	2.316
407	25.716	5.383	31.099
433	2.186	0.166	2.352
454	1.683	0.233	1.916
468	0.943	0.096	1.039

Attenuation due to water and non chlorophyll-like substances

Values of K_0 in the Bransfield Strait were higher than those in the waters of South Georgia (Table IV). The South Georgia values are comparable with published values for the Southern Ocean and other geographical areas, whereas the Bransfield Strait values are almost double these published values (Table II). In the South Georgia area K_0 increased with increasing wavelength, which is the expected relationship when only water attenuates radiance. However in the Bransfield Strait, the value

Table IV. Values of attenuation per unit pigment, K_c (m² (mg chl)⁻¹) and attenuation due to water and non chlorophyll-like substances, K_0 (m⁻¹) from this study showing the effect of the outlier on values of K_c and K_0 .

Wavelength (nm)	K_c	SE of K_c	K_0	SE of K_0	r^2	Area
444	0.00299	0.00102	0.0761	0.0295	0.84	South Georgia and Bransfield Strait
521	0.00945	0.00067	0.0707	0.0193	0.94	
552	0.00688	0.00098	0.0994	0.0283	0.80	
596	0.00790	0.00076	0.1367	0.0219	0.90	
444	0.00929	0.00405	0.0726	0.0278	0.32	South Georgia and Bransfield Strait minus high values at station 407
521	0.00432	0.00247	0.0803	0.0169	0.22	
552	0.00710	0.00431	0.0989	0.0296	0.20	
596	0.00630	0.00331	0.1396	0.0227	0.25	
444	0.00989	0.00167	0.0557	0.0112	0.83	South Georgia only
521	0.00426	0.00098	0.0714	0.0065	0.72	
552	0.00617	0.00129	0.0855	0.0087	0.75	
596	0.00612	0.00258	0.1280	0.0173	0.39	
444	0.00165	0.00082	0.1040	0.0216	0.90	Bransfield Strait only
521	0.00926	0.00071	0.0842	0.0189	0.97	
552	0.00605	0.00124	0.1250	0.0328	0.82	
596	0.00734	0.00062	0.1560	0.0164	0.96	
444	-0.01762	0.01293	0.1550	0.0189	0.38	Bransfield Strait minus high values at station 407
521	-0.00258	0.01322	0.1093	0.0193	0.01	
552	0.01378	0.02554	0.1091	0.0373	0.09	
596	0.00014	0.01229	0.1715	0.0179	0.00	

of K_0 at 444 nm was higher than that at 521 nm indicating that a non chlorophyll-like substance was also attenuating radiance. Attenuation due to non chlorophyll-like substances can be expressed by:

$$K_G G = K_0 - K_w \quad (2)$$

where, K_G = attenuation due to non chlorophyll-like substances (m² mg⁻¹)

G = concentration of non chlorophyll-like substances (mg m⁻³)

K_w = attenuation due to pure water (m⁻¹)

Since there is no site-specific measure of the value of G in this study, the value of $K_G G$ was taken as a constant for each site. Attenuation due to non-chlorophyll pigments around South Georgia had similar spectral properties to the attenuation due to Gelbstoff (Table VI), whereas the Bransfield Strait sites exhibited a secondary peak at 552 nm. The reason for this peak is not known, but the high attenuation at 444 nm indicates attenuation by Gelbstoff in this particular region of the spectrum, and is twice as high as that in the South Georgia area.

Gelbstoff is dissolved organic material which is derived either from the degradation of marine plants or may be of terrestrial origin (Kirk 1983). The waters of the Bransfield Strait and the Gerlache Strait can support large phytoplankton blooms (Estrada 1987, Heywood & Priddle 1987, and Mullins & Priddle 1987), and the degradation of these blooms may well provide a large concentration of Gelbstoff.

Mitchell (1992) reported Gelbstoff to be present in the Southern Ocean with values of $K_G G$ comparable to those in Table VI, ranging from 0.035–0.079 at 441 nm, 0.009–0.035 at

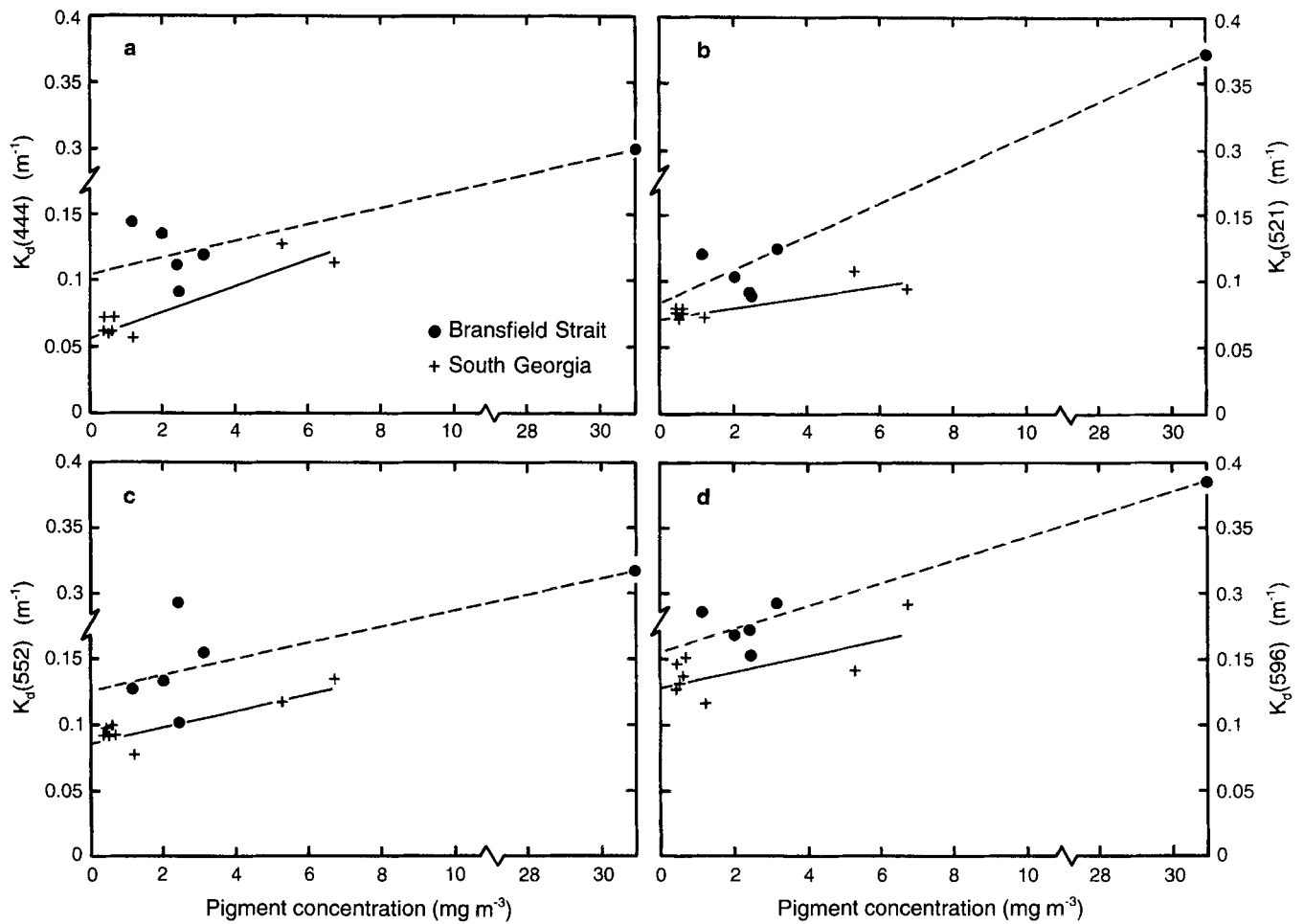


Fig. 2. Regression of attenuation coefficient ($K_d(\lambda)$) on pigment concentration at wavelengths of a. 444 nm, b. 521 nm, c. 552 nm, and d. 596 nm for South Georgia and the Bransfield Strait. Regression for 670 nm is not shown as it was highly variable.

520 nm and 0.011–0.029 at 560 nm. In this study negative values were obtained at 596 and 670 nm when K_0 for a particular wavelength was lower than that used for the attenuation coefficient of water at that wavelength. This occurs due to internal sources such as Raman scattering (Stavn & Weidmann 1990) and pigment fluorescence (Gordon 1979).

Attenuation due to non chlorophyll-like substances may also be due to scattering by inorganic particles i.e. sediments. The presence of inorganic particles in the water column of the Bransfield Strait has been shown by Wefer *et al.* (1988) from

sediment traps moored in the Bransfield Strait. They suggested that there was an increase in the supply of dust or mud to the water in the summer. The source of this inorganic material could be glacial melt water from the Peninsula and the surrounding islands (Mitchell & Holm-Hansen 1991b).

Table V. Results of Student's *t* test to compare the slopes (K_0) and intercepts (K_w) at each waveband for the two study sites.

Wavelength (nm)	Value of <i>t</i> for slope	Value of <i>t</i> for intercept
444	4.947*	23.089*
521	2.674	2.650
552	0.407	21.984*
596	0.333	10.859*

For the slope or intercept to be significantly different at $p < 0.001$ the value of *t* must be greater than 4.587.

Table VI. Values of $G_0 G$ from South Georgia and Bransfield Strait calculated using K_w from Morel (1988).

Wavelength	K_0	K_w	$G_0 G$
South Georgia			
444	0.057	0.017	0.041
521	0.072	0.049	0.023
552	0.086	0.064	0.022
596	0.128	0.253	-0.125
670	0.465	0.430	0.035
Bransfield Strait			
444	0.105	0.017	0.088
521	0.080	0.049	0.031
552	0.125	0.064	0.061
596	0.155	0.253	-0.098
670	0.361	0.430	-0.069

Implications for remote sensing

With the use of upwelled radiance data from the Southern Ocean, Mitchell & Holm-Hansen (1991a) found that the pigment retrieval algorithm developed for temperate regions underestimated chlorophyll concentration by 30–50% which they attributed to the small values of K_c found in the Southern Ocean. Thus Mitchell & Holm-Hansen (1991a) confirmed the need for pigment retrieval algorithms at the level of biogeographical regions.

The small values of K_c found in the two areas studied and the high values of K_d found in the Bransfield Strait suggest that within a biogeographical region, areas can be sub-divided into biogeochemical provinces on the basis of their unique optical properties. This implies that there is a requirement for pigment retrieval algorithms at the level of biogeochemical province if data from the forthcoming SeaWiFS mission are to be utilized to their full potential.

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References

- ATLAS, D & BANNISTER T.T. 1980. Dependence of mean spectral extinction coefficient of phytoplankton on depth, water colour, and species. *Limnology and Oceanography*, **25**, 157-159.
- BODUNGEN, B. VON, SMETACEK, V., TILZER, M.M. & ZEITZSCHEL, B. 1986. Primary production and sedimentation during spring in the Antarctic Peninsula region. *Deep-Sea Research*, **33**, 177-194.
- ESTRADA, M., 1987. Biomasa y producción fitoplanctónica en el Mar de Weddell y costas de la Península Antártica. In *Primer Simposio Español de Estudios Antárticos*. Madrid: Consejo Superior de Investigaciones Científicas, 175-191 pp.
- FALKOWSKI, P.G., DUBINSKY, Z., & WYMAN, K. 1985. Growth-irradiance relationships in phytoplankton. *Limnology and Oceanography*, **30**, 311-321.
- GORDON, H.R. 1979. Diffuse reflectance of the ocean. The theory of its augmentation by chlorophyll *a* fluorescence at 685nm. *Applied Optics*, **18**, 1161-1166.
- HAYES, P.K., WHITAKER, T.M., & FOGG, G.E. 1984. The distribution and nutrient status of phytoplankton in the Southern Ocean between 20° and 70° W. *Polar Biology*, **3**, 153-165.
- HEYWOOD, R.B. 1985. Environmental conditions in the Antarctic Peninsula area of the Southern Ocean during the Anglo-German joint biological expedition, February 1982. *Meeresforschung*, **30**, 220-239.
- HEYWOOD, R.B. & PRIDDLE, J. 1987. Retention of phytoplankton by an eddy. *Continental Shelf Research*, **7**, 937-955.
- HOLM-HANSEN, O. & MITCHELL, B.G. 1991. Spatial and temporal distribution of phytoplankton and primary production in the western Bransfield Strait region. *Deep-Sea Research*, **38**, 961-980.
- JERLOV, N.G. 1968. *Optical oceanography*, Elsevier Oceanography Series, 5. Amsterdam: Elsevier, 194 pp.
- KIRK, J.T. 1983. *Light and photosynthesis in aquatic ecosystems*. Cambridge: Cambridge University Press. 401 pp.
- MITCHELSON, E.G., JACOBS, N.J. & SIMPSON, J.H. 1986. Ocean colour algorithms from the case 2 waters of the Irish Sea in comparison with case 1 waters. *Continental Shelf Research*, **5**, 403-415.
- MITCHELL, B.G. 1992. Predictive bio-optical relationships for polar oceans and marginal ice zones. *Journal of Marine Systems*, **3**, 91-105.
- MITCHELL, B.G. & HOLM-HANSEN, O. 1991a. Bio-optical properties of Antarctic waters: Differentiation from temperate ocean models. *Deep-Sea Research*, **38**, 1009-1028.
- MITCHELL, B.G. & HOLM-HANSEN, O. 1991b. Observations and modeling of the Antarctic phytoplankton crop in relation to mixing depth. *Deep-Sea Research*, **38**, 981-1007.
- MOREL, A., 1988. Optical modeling of the upper ocean in relation to its biogenous matter content (case I water). *Journal of Geophysical Research*, **93**, 10749-10768.
- MULLINS, B.W. & PRIDDLE, J. 1987. Relationship between bacteria and phytoplankton in the Bransfield Strait and South Drake Passage. *British Antarctic Survey Bulletin*, No. 76, 51-64.
- NELSON, D.M. & GORDON, L.I. 1985. Phytoplankton dynamics of the marginal ice zone of the Weddell Sea, November and December 1983. *Antarctic Journal U.S.*, **19**, 105-107.
- PLATT, T., CAVERILL, C. & SATHYENDRANATH, S. 1991. Basin-scale estimates of oceanic primary production by remote sensing: The North Atlantic. *Journal of Geophysical Research*, **96**, 15147-15159.
- PLATT, T. & JASSBY, A.D. 1976. The relationship between photosynthesis and light for natural assemblages of coastal marine phytoplankton. *Journal of Phycology*, **12**, 421-430.
- PRIDDLE, J., HEYWOOD, R.B., THERIOT, E. 1986. Some environmental factors influencing phytoplankton in the Southern Ocean around South Georgia. *Polar Biology*, **5**, 65-79.
- PRIDDLE, J., SMETACEK, V. & BATHMANN, U. 1993. Antarctic marine primary production, biogeochemical carbon cycles and climate change. *Philosophical Transactions of the Royal Society of London*, **B 338**, 289-297.
- SIEGAL, D.A. & DICKEY, T.D. 1987. On the parameterization of irradiance for open ocean photoprocesses. *Journal of Geophysical Research*, **92**, 14648-14662.
- SMITH, R.C. & BAKER, K.S. 1978a. The bio-optical state of ocean waters and remote sensing. *Limnology and Oceanography*, **23**, 247-259.
- SMITH, R.C. & BAKER, K.S. 1978b. Optical classification of natural waters. *Limnology and Oceanography*, **23**, 260-267.
- STAVN, R.H. & WEIDENMANN, A.D. 1988. Optical modeling of clear ocean light fields: Raman scattering effects. *Applied Optics*, **27**, 4002-4011.
- STRAMSKI, D. & MONTWILL, K. 1982. Light conditions in the Antarctic water of the Drake Passage and the South Shetland Islands region during summer 1981. *Polish Polar Research*, **3**, 153-170.
- TAYLOR, N.K. 1992. The role of the ocean in the global carbon cycle Part 1: The marine carbon pumps. *Weather*, **47**, 146-151.
- WEFER, G., FISCHER, G., FUEITTERER, D. & GERSONDE, R. 1988. Seasonal particle flux in the Bransfield Strait, Antarctica. *Deep-Sea Research*, **35**, 891-898.
- WHITEHOUSE, M.J., SYMON, C.J. & PRIDDLE, J. 1993. Variation in the distribution of chlorophyll *a* and inorganic nutrients around South Georgia, South Atlantic. *Antarctic Science*, **5**, 367-376.