Interpretation of multi-season, multi-year colour imagery for a continental shelf region

Shelf sea
Remote sensing
Turbidity

Eaux continentales
Télédétection
Turbidité

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ABSTRACT

A comparison was made between multi-year, multi-season cruise information from the surface waters of the Scotian shelf and satellite imagery from the Coastal Zone Colour Scanner (CZCS). The colour imagery was able to identify several physical processes on the shelf (such as outflows and upwelling) to approximately the same degree as previously reported with thermal imagery. Because processing CZCS data requires the use of atmospheric and marine models defined by a range of input parameters, the various processing steps and assumptions were evaluated for potential impact on any marine interpretation of the imagery. The shelf waters were not a pure oceanic water mass throughout the year and turbidity levels were found to be the most significant interfering factor in successful interpretation of the majority of the ocean colour imagery. During spring and autumn, possible bloom periods, pigment material began to dominate the optical environment and hence permitting pigment algorithms to successfully explain most of the variance observed in the satellite imagery. Although it was not possible to associate individual colour features on the shelf with particular in-water constituents, the long term trend in shelf water turbidity was related to the general level of biological material. As a consequence the satellite derived mean monthly levels of pigment material for the whole shelf were found to be in good agreement with the measured seasonal cycle.

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RÉSUMÉ

Interprétation d'une imagerie en couleur plurisaisonnière et pluriannuelle pour une région de la plate-forme continentale

Une comparaison a éte faite entre des données de campagnes pluriannuelles et plurisaisonnières portant sur les eaux de surface de la plate-forme néo-écossaise et des images satellitaires en provenance du Coastal Zone Color Scanner (CZCS). L'imagerie en couleur a permis d'identifier plusieurs processus physiques sur la plate-forme (comme les écoulements et les remontées d'eau) avec à peu près le même degré de qualité que préalablement signalé par une imagerie thermique. Parce que le traitement des données CZCS nécessite le recours aux modèles atmosphériques et marins définis par une gamme de paramètres d'entrée, les diverses étapes et hypothèses de traitement ont été évaluées afin d'en déterminer les répercussions potentielles sur toute interprétation marine des images. Les eaux de la plate-forme ne sont pas restées une masse d'eau océanique pure pendant toute l'année, et l'on a constaté que les niveaux de turbidité constituaient le facteur d'interférence le plus déterminant dans une interprétation réussie de la majorité des images de couleur de l'océan. Au cours du printemps et de l'été, qui sont des périodes susceptibles de poussées phytoplanctoniques, la matière pigmentaire a commencé à dominer le milieu optique, permettant ainsi aux algorithmes pigmentaires d'expliquer avec succès la majeure partie de la variance observée dans l'imagerie par satellite. Bien qu'il n'ait pas été possible d'associer des structures de couleur distinctes sur la plate-forme avec des constituants particuliers dans l'eau, la tendance à long terme de la turbidité des eaux de la plate-forme a été rapprochée du niveau général de concentration en matériel biologique. Par conséquent, les auteurs ont constaté que les niveaux mensuels moyens de matière pigmentaire (déduits par satellite) pour l'ensemble de la plate-forme correspondaient bien au cycle saisonnier mesuré.

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INTRODUCTION

Continental shelves play an important role in the biological fertility of the oceans and are often critical to coastal fisheries resources. The Scotian shelf is one such area with a complex topography of banks and basins (Fig. 1) which are thought to act as both feeding and breeding grounds for numerous species from zooplankton to fish (Fournier *et al.*, 1977; Mills and Fournier 1979). The general circulation processes and patterns of the Scotian shelf are thought to be understood (Sutcliffe *et al.*, 1976; Drinkwater *et al.*, 1979) but several sources act as the origin of waters on the shelfs (Drinkwater and Trites, 1987) divided the shelf and slope area into 37 regions as determined by the annual cycle of salinity and temperature for each area. The outflow of the Gulf of St. Lawrence passes around the north of Nova Scotia and mixes with slope water to form Scotian shelf water and a current along the Nova Scotia coast largely confined to the inner 80 km of the shelf (Drinkwater *et al.*, 1979; *see* Fig. 1). Because of the possible significance of shelf topography, the area has received considerable attention often highlighting the complex nature of the processes taking place (McLellan, 1957; Horne, 1978; Houghton *et al.*, 1978; Smith *et al.*, 1978; Petrie and Smith, 1979; Smith and Petrie, 1982).

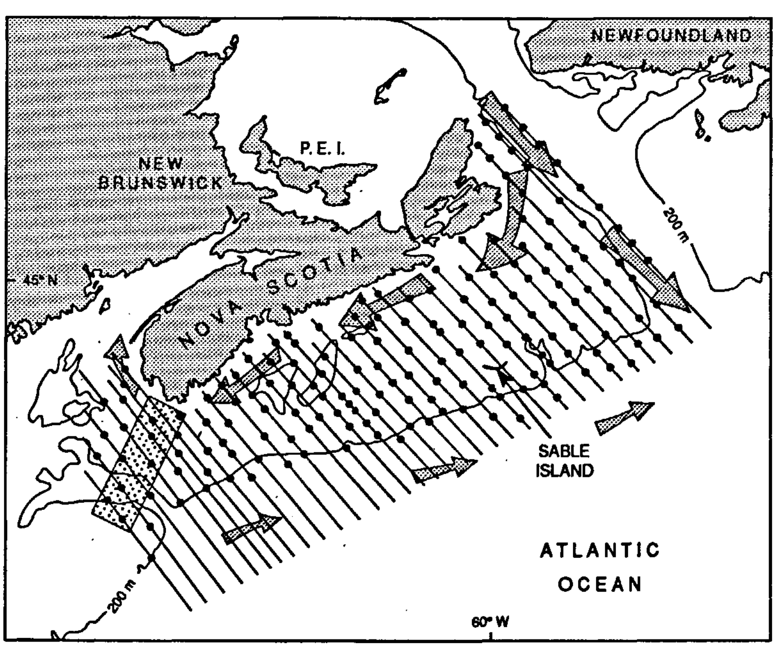

Figure 1

Location map showing bathymetry and major currents on the Scotian shelf. Station grid for cruise sampling; shaded box gives location of optical stations.

Carte de localisation montrant la bathymétrie et les principaux courants sur le plateau écossais. Quadrillage des stations pour l'échantillonnage de la mission ; la case ombrée indique l'emplacement des stations optiques.

Some of the physical manifestations of these circulation processes have been observed in satellite imagery, particularly by thermal infrared (IR) sensors which can monitor sea surface temperature. As the Nova Scotia current turns the southern tip of Nova Scotia, it interacts with tidal forces (Garrett and Louck, 1976; Smith, 1983) to produce a semi-permanent region of upwelling. For much of the year this region exhibits a sufficiently strong temperature gradient that it is regularly detectable in IR imagery. The main Nova Scotia current however produces a comparatively weak surface thermal gradient so that its detection in satellite imagery is both intermittent and far less obvious. Only under specific physical conditions do the thermal signatures become sufficiently strong that they can be seen in satellite imagery; two such examples are a surface front associated with strong alongshore transport of water out of the Gulf of St. Lawrence (Petrie, 1987) and wind-induced upwelling (Petrie *et al.*, 1987). At given times the southwest shelf edge can come under the influence of Gulf Stream warm core rings, and IR imagery has shown occasional indication of intrusion of surface water onto the shelf or extrusion of water off the shelf. However with the exception of Georges Bank in the Gulf of Maine, none of the banks and basins on the Scotian shelf have shown strong or easily detectable satellite thermal signatures.

Since 1978 ocean colour imagery has been available from the CZCS (Coastal Zone Colour Scanner) on board the Nimbus-7 satellite. Colour imagery has already been used to describe ocean features of interest to both physical and biological oceanographers (Abbott and Zion, 1985; Brown *et al.*, 1985). Ocean colour sensing also has two potential advantages over IR sensing. Firstly, it can detect radiation from a greater physical depth in the ocean, typically from the top ten metres for a shelf sea rather than from the top millimeters of the sea surface. This means that colour imagery can sometimes see a subsurface water mass before the corresponding thermal signature has reached the surface (Irish Sea fronts, pers. comm. Prof. Simpson, U.K.). Secondly, although both types of ocean sensing depend on detecting gradients of a parameter which provide information about dynamic processes, in areas where the temperature field is fairly uniform visible images have been shown to identify eddy structures not evident in IR imagery (Robinson, 1985).

For the current generation of ocean colour satellite sensors the reliable prediction of concentrations of water constituents is restricted to well-defined interpretation limitations (Gordon and Morel, 1983). Although the archives of the Coastal Zone Colour Scanner (CZCS) span from 1979 to 1986 and are presently the largest database of optical information for the world's oceans, covering open ocean areas as well as shelf and coastal regions, not all these regional images will comply with the limitations for interpreting data. In addition, in many cases insufficient optical information is available to predetermine whether the sensor/interpretation limitations apply. Interpretation models for ocean colour imagery have allowed estimation of biological pigment levels for open ocean (or case 1) waters (Morel and Prieur, 1977). Methodologies for the interpretation of other water masses remains the subject of active research. In some studies (Bricaud and Morel, 1987; Gordon *et al.*, 1988) optical water models are used to separate the cases 1 and 2 water masses, with case 2 (usually non-oceanic) imagery being discarded or masked out (by inferred definition case 2 waters are all those which do not fit a case 1 biological pigment model). In other studies where suspended sediments have dominated the coastal environment, general turbidity models have been used to interpret coastal imagery (Sturm, 1981; Sturm, 1983; Viollier and Sturm, 1984). In some shelf sea areas where the suspended sediment and pigment loads have co-varied, regional optical pigment algorithms have been employed (Mitchelson *et al.*, 1986). Studies for other shelf and coastal areas have indicated the limitations in deriving colour imagery algorithms (Simpson and Brown, 1987).

In this paper CZCS colour imagery from 1979 to 1982 has been examined from the perspective of the extent to which the uncertainty in specification of the sensor degradation and atmospheric correction routines affect the ability of interpreted imagery to correctly represent the spatial and temporal distribution of material for the continental shelf area off Nova Scotia. With the use of shipboard data from the Scotian Shelf Ichthyoplankton Programme (SSIP, O'Boyle *et al.*, 1984) conducted from 1978 to 1982 a comparison was made with the seasonal levels of satellite predicted concentrations. The aims of this paper are: 1) to determine whether ocean colour imagery can detect any of the circulation and physical processes on the Scotian shelf; 2) to determine to what extent, if any, such processes can be quantified by a single optical, biologically dominated, parameter model; and 3) to determine to what extent non-oceanic (case 2) imagery can still yield useful information.

DATA AND METHODS

In situ water sample data

The Scotian Shelf Ichthyoplankton Programme (SSIP) was operated by the Canadian Department of Fisheries and Oceans to provide basic information on the spatial and temporal distribution of fish eggs and larvae on the Scotian shelf as an aid to better management of the fishery. The sampling grid established consisted of 150 stations with an inter-station spacing of approximately 30 km (Fig. 1). The grid was sampled as often as possible between 1978 and 1982 during which fish eggs and larvae were sampled together with surface data on nutrients (silicates, phosphates and nitrates), chlorophyll and zooplankton. Some basic hydrographic observations (temperature, salinity and Secchi disc) were made at most stations. The full details of sample collection and analysis are outlined in O'Boyle *et al.* (1984). The chlorophyll samples were collected in triplicate using Whatman GF/C filters but the phaeophytin data were only retained for a minority of the stations. The temperature values were taken from bucket samples and reversing thermometers and the Secchi disc values were logged as integer metres. In total there were five cruises in 1978, seven in 1979, eight in 1980 plus three very localized or "patch study" cruises, and four cruises in each of 1981 and 1982. Not all the cruises were able to cover the entire grid or make the full suite of in situ observations. Hence much of the available information was in overlapping subsets.

Of this data set the primary parameters suitable for correlation with interpreted satellite visible imagery are the surface chlorophyll levels, the Secchi disc measurements and the sea surface temperatures. For inter-comparing ocean feature detection by thermal and colour satellite imagery, it was useful to determine the degree of covariance between the shipboard surface measurements

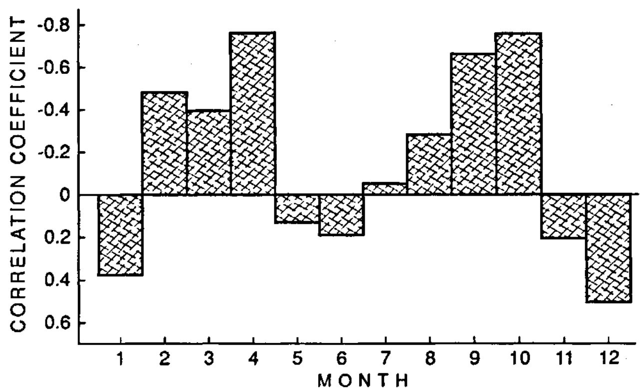

Figure 2

The inter-correlation between chlorophyll (logarithmic form) and temperature data combined for all stations and all years for each calendar month.

Inter-corrélation entre les données sur la chlorophylle (forme logarithmique) et les données sur la temperature, combinées pour toutes les stations et toutes les années, pour chaque mois civil.

of temperature and chlorophyll. The individual cruises showed varying degrees of correlation between surface temperature and chlorophyll depending on exact dates and spatial coverage; however when all the cruise data were combined into monthly segments, regardless of year, a strong seasonal variation in the correlation was observed (Fig. 2). The spring and autumn months had a significant negative correlation with temperature while the remaining months had a weak, non-significant and occasional positive correlation. This implies that during spring and autumn, the higher concentrations of chlorophyll pigment were associated with the cooler inshore waters; for the rest of the year there is no such distinct patterns with temperature. The Secchi disc measurements, however did not demonstrate the same seasonal pattern. The correlation between temperature and Secchi disc was lower and statistically less significant throughout the year. This implies that covariance between water turbidity patterns and thermal patterns at all times of the year could not necessarily be associated with biological activity.

Satellite colour algorithms provide an estimate of "total" pigment concentration defined as the sum of chlorophyll *a* and phaeophytin concentrations. The detrital component of marine chlorophyll may have a much higher absorption coefficient at the blue end of the spectrum than that from chlorophyll alone (Prieur and Sathyendranath, 1981; Topliss *et al.*, 1989 *a*) and under certain conditions detrital material could significantly affect the reflectance as seen by ocean colour satellites (Topliss, 1989). Because most of the SSIP stations had no detrital estimates samples from a subset of 1,000 stations with both chlorophyll and phaeophytin values were examined.

The proportion of phaeophytin to total pigment reached a maximum at approximately 30-40 % for pigment concentrations below 1 mg/m^3 decreasing to about 15 % for values of pigment greater than 5 m/m^3. This increase in detrital proportion at low concentrations is in agreement with previous studies (Hobson *et al.*, 1973; Smith and Baker, 1978). A strong linearity (R^2 of 98.5 %, slope 1.1) between total pigment and chlorophyll existed for surface samples taken from all periods of the year; so that although satellite/sea truth comparisons might differ in absolute units, they would be expected to co-vary. The estimates given by satellite algorithms are also depth-integrated values (Smith and Baker, 1982) since the satellite sensor "sees" down to approximately one optical depth. The effect of using surface as opposed to depth integrated pigment estimates was also examined for a subset of SSIP stations by Topliss *et al.* (1988). Again a strong covariance existed between the two estimates indicating no strong optical vertical stratification within the depths monitored by satellites (typically 5 to 20 m). This type of analysis does not rule out seasonal stratification at greater depths within the photic zone.

In situ optical data

The Secchi disc measurements provided the only *in situ* optical data for the Scotian shelf for the period 1979 to 1982. The relationship between the Secchi disc measurements and other *in situ* optical measurements has been outlined in Tyler (1968), Gordon and Wouters (1978) and Preisendorfer (1986). Empirical relationships, derived between Secchi disc values and the optical properties/characteristics of a water mass, have also been shown to vary with water mass type (Holmes, 1979; Topliss, 1982 *a*).

Table 1

Local optical relationships.

Caractéristiques optiques locales.

All data		
	$C = 1.2\,R_{13}^{-2.7}$	$R^2 = 0.76$, n = 49
	$C = 2.9\,R_{23}^{-6.4}$	$R^2 = 0.80$, n = 49
$C < 1.5$ mg m^{-3}		
	$C = 0.88\,R_{13}^{-3.2}$	$R^2 = 0.71$, n= 14
$C > 1.5$ mg m^{-3}		
	$C = 3.7\,R_{23}^{-4.0}$	$R^2 = 0.79$, n = 35
Turbidity: iteration schemes		
Austin and Petzold (1980):		
	$R_{14} = 5.3\,R_{13}^{2.3}$	$R^2 = 0.78$, n = 26
Sturm (1983): fitted		
	$L_{ss4} = L_{ss3}\,10^{-(0.6+1.0 \log f)}$ where f is given in Sturm (1983)	
Suspended matter		
	$SS = 0.76\,C^{0.37}$	$R^2 = 0.71$, n = 52
where	C = chlorophyll like pigments in mg/m^3 SS= suspended sediment concentration in mg L^{-1} L_{ssx} =subsurface radiance at wavelength x R_{xy}= ratio of reflectances at wavelengths x and y x, y = 1, 2, 3, 4 the four CZCS channels at 443, 520, 550 and 670 nm.	

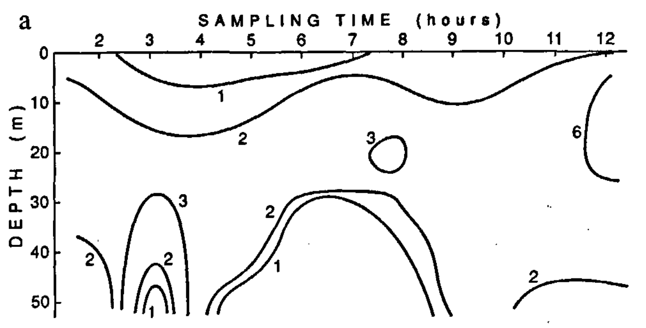

Figure 3 *a*

Depth-time contours of chlorophyll-like pigments over a tidal cycle at a fixed optical station.

Isolignes profondeur-temps des pigments chlorophylliens au cours d'un cycle de marée dans une station optique donnée.

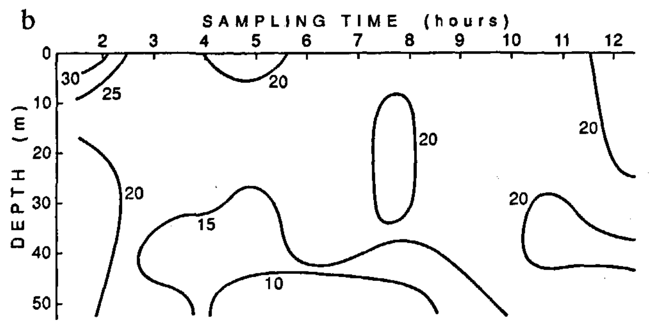

Figure 3 *b*

Depth-time contours of dissolved organic indicator (see *text*) *over a tidal cycle at a fixed optical station.*

Isolignes profondeur-temps de l'indicateur de matière organique dissoute (*voir* texte) au cours d'un cycle de marée dans une stations optique donnée.

An insight into the expected characteristics of the *in situ* optical data in the shelf region is provided by the spatially-limited data obtained from the south-west corner of the study area (*see* box section in Fig. 1) in late July 1985. This data set consisted of irradiance reflectance measurements at eleven wavelengths from a MER 1000 spectroradiometer (Topliss, 1989 *a*; 1989 *b*) along with samples for chlorophyll plus phaeophytin and dissolved organic fluorescence measurements (Topliss, 1989 *b*) at approximately ten depths and suspended sediment dry weight data at three depths per station. The CZCS ratio algorithms (443/550 and 520/550) derived from these data, Table 1, gave marginal agreement with oceanic algorithms and have lower correlation coefficients. In previous similar studies Gordon and Morel (1983) interpreted such lower correlations as due to the presence of non-case 1 water constituents.

Examination of the *in situ* sediment and dissolved fluorescence data also provided some support for a non-case 1 water mass. The suspended sediment concentration levels were in excess of those predicted for an oceanic environment using the relationship of Gordon and Morel (1983), although a strong correlation ($r = 0.84$) with pigment levels remained (*see* Tab. 1). The dissolved organic fluorescence (DOF) values had no significant relationship with either chlorophyll or suspended sediment in correspondence with DOF data acquired in two surface tracks, across chlorophyll fronts off south-west Nova Scotia. Even for observations of distinct tidal changes in the depth profile of dissolved fluorescence (Fig. 3), for fixed stations maintained over a tidal cycle, again DOF did not co-vary with either the corresponding chlorophyll or available nutrient data during the tidal cycle. Other optical relationships examined also showed differences from pure oceanic conditions (*see* Tab. 1). Although the field values of a 520/550 ratio were comparable to those of Austin and Petzold (1980) over a similar total pigment range, the 443/520 ratio had a much smaller range possibly due to the presence of dissolved material affecting the blue end of the spectrum.

A full spectral investigation of the *in situ* constituents was made using all potential spectral ratios rather than just the CZCS ratios. The eleven channels of the MER 1000 were used to form logarithmic ratios of reflectance for the wavelengths between 380 and 710 nm; these log ratios were then regressed against the total pigment (log) values and the amount of explained variance was expressed as a percentage. These results are presented graphically in Figure 4 *a*. The positions of the standard CZCS ratios (443/550 and 520/550) are shown for reference. The optimum region of the spectrum for explaining pigment concentrations is between 480 and 560 nm, shifted slightly away from the CZCS ratios. Since the analysis is purely a statistical one, the variance in pigment concentrations used for Figure 4 *a* will also include all statistically co-varying additional material, both organic and inorganic, whose unknown contribution may add to a shift away from the CZCS wavelengths. After elimination of the pigment contribution to the variance, the regression analyses were repeated to estimate any residual variance which co-varied with either dissolved material indicators (DOF values) (Fig. 4 *b*) or suspended dry weight (Fig. 4 *c*): Figures 4 *b* and 4 *c* can be obtained with either a partial correlation analysis (Johnston, 1978) or with a multiple regression analysis (Johnston, 1978) which includes pigment as the first independent variable and then looks at the amount of additional variance explained by adding dissolved organics for Figure 4 *b* and by adding sediment load for Figure 4 *c*. Although the additional explained variance from these analyses was relatively low (15, 20 and 30 %), the spectral position of the maximum correlation was highly significant. Figure 4 *b* shows that variance associated with the chlorophyll-subtracted co-varying component of the dissolved organic fluorescence values was completely limited to the blue (short wavelength) region of the spectrum, while the chlorophyll-subtracted co-varying component of suspended sediment dry weight values explained variance at the red (long wavelength) end of the spectrum. These residual spectral distributions are "classic" for non-case 1 conditions. Unfortunately no *in situ* data are available to describe possible seasonal and regional variation of these residuals in the shelf region.

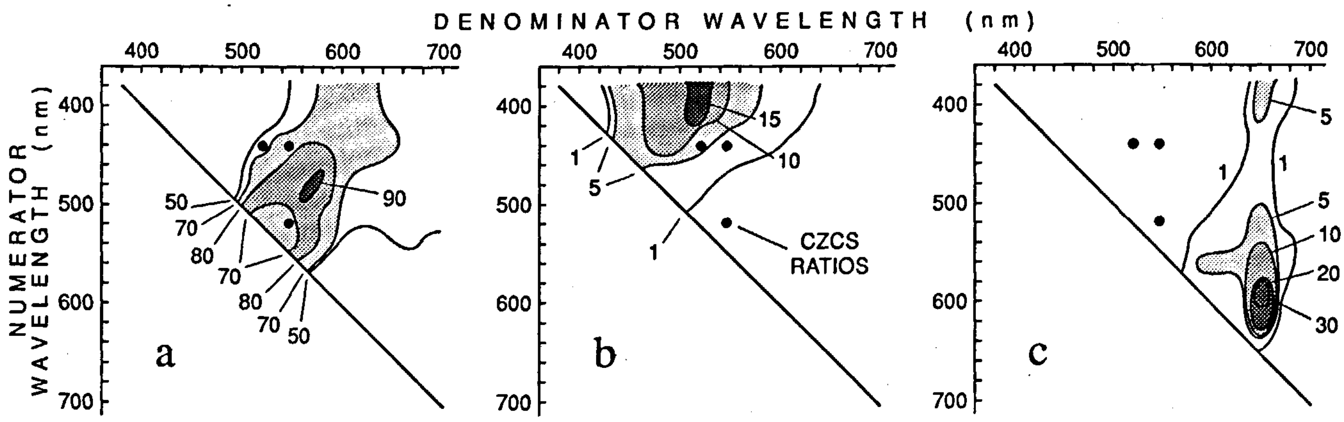

Figure 4 *a*

Percentage of explained variance between chlorophyll-like pigments (logarithmic form) and the logarithmic ratio of reflectance for pairs of wavelengths between 380 and 700 nm.

Pourcentage de variance expliquée entre les pigments chlorophylliens (forme logarithmique) et le rapport logarithmique de réflectance pour des paires de longueurs d'onde entre 380 et 700 mn.

Figure 4 *b*

Spectral distribution of explained variance (%) between ratio of wavelength and dissolved organic indicator (log-log form) after removal of chlorophyll-like pigment variance.

Distribution spectrale de la variance expliquée (%) entre le rapport de longueur d'onde et l'indicateur de matière organique dissoute (forme log-log) après défalcation de la variance des pigments chlorophylliens.

Figure 4 *c*

Spectral distribution of explained variance (%) between ratio of wavelength and suspended sediment concentration (log-log form) after removal of chlorophyll-like pigment variance.

Distribution spectrale de la variance expliquée (%) entre le rapport de longueur d'onde et la concentration de sédiments en suspension (forme log-log) après défalcation de la variance des pigments chlorophylliens.

Satellite data

The CZCS sensor calibration started to degrade soon after launch and numerous scientific studies have evaluated decay formulae (Viollier, 1982; Gordon *et al.*, 1983; Meuller, 1985). Level 1 CZCS satellite images were selected from the NOAA/EDIS archive of data for all good quality images coincident with the cruise dates. Considerable cloud cover existed for the winter months limiting the quantity of useful imagery. Cloud cover also commonly existed related to particular weather systems such as strong offshore cloud layers. However, enough cloud free imagery was found to cover all the months/seasons except for November and December, although seasonal coverage sometimes required imagery from different years. In total, fifty good images were examined from which regions of cloud free information could be related to the cruise data. Because the survey vessel took up to three weeks to survey the whole shelf whereas the satellite took less than three minutes to cover an even wider area; there were few truly coincident ground control points. For same day coverage, approximately 22 cloud free, low error (*see* later section) coincident image values were obtained (only 1 % of the available cruise information). Additional ways of exploiting the non-coincident cruise information were hence explored.

CZCS PROCESSING

The implications of CZCS characteristics and the scientific basis of the standard CZCS processing stages are given by several authors (Gordon, 1978; Gordon and Clark, 1981; Sturm, 1981; Gordon and Castano, 1987). This study is concentrated on the potential impact of different assumptions in each processing stage on the final marine interpretation of the Scotian shelf images. These processing stages, together with differences in approach for interpreting colour images, are given in Table 2.

Image data extraction

The CZCS images were primarily processed using several versions (1986-1990) of the RSMAS, University of Miami software package with some comparative analyses being conducted on software developed at York University, Toronto. Images were processed with various combinations of the assumptions and options outlined in Table 2 and processing completed to give all the atmospherically-corrected water-leaving radiances as well as a predicted total pigment image. Data were extracted from these images at the corresponding SSIP survey station latitude and longitudes for a single pixel value and for a 5 by 5 pixel average plus standard deviation. The latter error value was used to eliminate highly variable data caused either by inter-pixel cloud contamination (Robinson, 1985) or by close proximity to a discontinuity such as an ocean front. The satellite data sets extracted under different processing assumptions were combined with the *in situ* station data and evaluated for degree of covariance. The combined file also contained all the "housekeeping" information such as image and station date and time of day so that time difference and time of day windows could be examined.

Data interpretation/analysis trials

The small number of same day (zero day difference) image/sea data pairs (22) gave a very low correlation (r =

Table 2

CZCS processing stages.

Étapes d'analyse de données CZCS.

ROUTINE	DESCRIPTION	COMMENT and LIMITATIONS
Sensor characteristics		
SENSOR: DEGRADATION		
Long period	Formulae review given by Sturm (1983)	Mainly extrapolation after orbit 2000. Correction methods model dependent.
Short period	Gordon and Evans (1990)	Large variations after late 1981.
SENSOR CHARACTERISTICS		
Gain	Non-uniformities between gains. Experience: gain 4 images no longer released	Low light level or winter imagery suspect.
Hysteresis/ringing	Enlarged "cloud" masks used to eliminate areas affected	
Atmospheric correction models		
SOLAR CONSTANTS	Neckel and Labs (1981; 1984) adaptations for CZCS bandwidths (Gordon, 1986; 1988)	Choice altered absolute value of predicted pigment concentrations but had minimal effect on satellite-sea truth correlations.
RAYLEIGH CORRECTION	Single scattering and multiple scattering	Poorer estimates at latitudes above 45°
OZONE CORRECTION	Seasonal and regional standards (McClatchey *et al.*, 1972). Measured values for each scene from TOMS (Total Ozone Mapping spectrometer; Nimbus7) conversion to optical coefficient Vigroux (1953)	Large diurnal changes in mid-Atlantic regions, TOMS satellite data also subject to sensor drift and correction schemes.
AEROSOL ESTIMATION	Individual scene correction Seasonal and geographic variations.	Requires clear water with low 550 nm signal. Summer continental air mass noted for images off US eastern seaboard.
Marine/atmospheric models		
ITERATION SCHEMES	Oceanic or case 1 no iteration, $L_w670 = 0$, Gordon (1978). Others: Austin and Petzold (1980), clear and turbid water (Sturm 1983). Locally determined, *see* Table 1.	Iteration schemes revealed low 670nm turbidity patterns on southern shelf. Spatially and temporally limited.
CLASSIFICATION SCHEMES	Case 1/2 separations Gordon *et al.* (1988), Bricaud and Morel (1987)	Requires pre-determined marine optical assumptions or model for each scene.
PIGMENT ALGORITHMS	NASA/NOAA formula with algorithm switch over at 1.5 mg/m^3 (Gordon and Clark, 1981). Algorithms reviews given in Gordon and Morel (1983), Mitchelson *et al.* (1986), Topliss *et al.* (1989 *a*).	

0.2) but by balancing an increase in the time difference window with lower error limits on the water leaving radiances, larger and significant data groups could be examined. Changing the models and assumptions for sensor characteristics and basic sun/atmosphere optical characteristics (solar constants, Rayleigh and ozone optical depths) caused changes in the absolute levels of predicted material but little variation in water colour patterns. The exceptions were with high gain (3 or 4) imagery, imagery with large scale variations in atmospheric patterns and winter imagery subject to either of the previous categories. Most of the imagery had already been preselected for

Table 3

Summary of data analysis trials.

Sommaire de l'analyse des données.

Possible improvements	
1. Seasons:	Subgrouping data by seasons
2. Function:	Different functional forms for algorithm
3. *In situ*:	Modelling or incorporating in situ parameters other than chlorophyll: Secchi disc
Possible improvements	
1. Atmosphere:	Seasonal variation for aerosol
2. Geography:	Examining data by geographic subdivisions
3. Type/case:	Using case 1/2 discrimination techniques (partially) to separate different water types
No observed improvements	
1. Temporal:	Reducing time-lag window to zero
2. Detrital:	Correcting chlorophyll values for phaeophytin contribution
3. Depth:	Correcting surface chlorophyll estimates for depth integration
4. Diurnal:	Separating off day and night *in situ* chlorophyll values
5. Range:	Adjusting the concentration range and cross-over point
6. Algorithm:	Using different or differing coefficients in the chlorophyll formulae
7. *In situ*:	Modelling or incorporating in situ parameters other than chlorophyll: salinity, nutrients, zooplankton

relatively clear atmosphere, gain 1 or 2 setting and 88 % were dated earlier than mid-1981 thereby minimizing the effects of short period sensor gain fluctuations (pers. comm. Evans, University of Miami). The aerosol corrections were applied both on a scene by scene basis and using assumed "standard" atmospheres. The analyzed images produced atmospheric optical characteristics consistent with clear "maritime" aerosols during winter and spring and higher "continental" aerosols during the summer months. Such a seasonal variation in aerosol type has previously been noted by Miami University (pers. comm. R. Evans).

The remaining water modelling assumptions in Table 2 were examined in conjunction with different analysis groups as given in Table 3. With such analyses, the failure of particular conditions/subgroupings to improve correlations also provided *post priori* information on marine conditions. In many cases more than one set of restrictions was applied so that although the individual categories in Table 3 can be discussed separately, a full analysis had to include an examination of all combinations of the groups. Table 3 summarizes the deductions from all the analyses.

Certain data groupings produced no improvements. Altering the time difference window, modelling the phaeophytin and depth variations to pigment concentration have already been discussed and produced no improvement in image/sea data correlation. Various ocean processes have been noted to have a diurnal feature; vertical migration of zooplankton (Ryther *et al.*, 1961), and diurnal changes in chlorophyll (Le Bouteiller and Herbland, 1982) which may influence optical properties (Postma and Spitzer, 1982). The CZCS algorithm has two forms, applied for concentration ranges less than and greater than 1.5 mg/m^3 (*see* also Tab. 1) and, for shelf sea areas, the cross-over point can vary as non-oceanic material alters the water leaving radiance. In some studies (Mitchelson *et al.*, 1986) the non-oceanic coefficients of the satellite algorithm have been derived and these coefficients were allowed to change for the different subgroups, particularly regional and seasonal changes.

Other studies have noted the exceptionally high scattering produced by coccolithophore blooms (Holligan *et al.*, 1983) and the impact of different biological species (Balch *et al.*, 1989) on satellite algorithms even for oceanic waters. Other parameters such as nutrient levels, salinity and zooplankton were unsuccessfully used both in multiple regression analyses in an attempt to explain additional variance and as aids to identify particular subgroups. Salinity can act as an indication of freshwater and in the autumn, low salinities (< 29) are associated with the outflow of the Gulf of St Lawrence. The nutrient and zooplankton levels can be indicators of the seasonal biological cycle. Lack of success using these parameters might indicate that there was no single seasonal co-varying relationship between in situ substances. Not all the data was overlapping however and the zooplankton net size was a 333 micron mesh size which did not net smaller sized animals, most possibly related to optical scattering.

Another group of tests did show some improvement in correlation. The seasonal changes in aerosol have already been discussed. If the presence of different water types were the cause of the low explained variance, an examination of different geographical areas of the shelf would be expected to provide some consistency. Although the 37 areas suggested by Drinkwater and Trites (1987) could be reduced to 11 (pers. comm. Petrie, BIO) this was still too many to obtain a good statistical range of values over the seasons. The final analysis was a simple onshore/offshore division which approximately followed

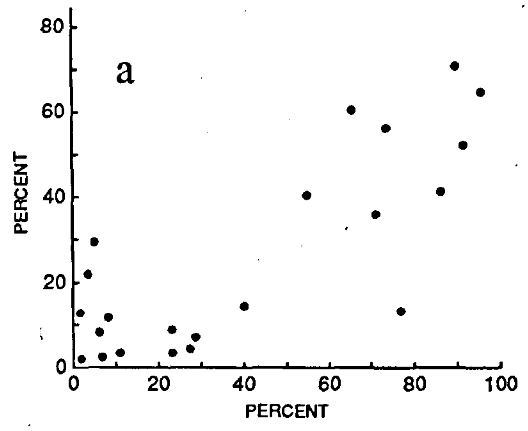

Figure 5 *a*

Percentage of covariance between satellite chlorophyll predictions and in situ *chlorophyll ranked by the degree of correlation (expressed as a %) between chlorophyll and for each subgroup of data trials (solid line 1:1).*

Pourcentage de covariance entre les prévisions de la chlorophylle par satellite et la chlorophylle *in situ* classée selon le degré de corrélation (exprimé en %) entre la chlorphylle et pour chaque sous-groupe de données (trait plein 1.1).

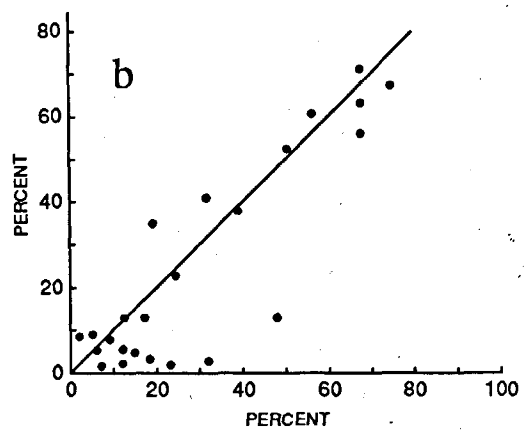

Figure 5 *b*

Percentage of covariance between satellite chlorophyll predictions and in situ *chlorophyll ranked by the degree of correlation (expressed as a %) between chlorophyll and Secchi disc for each subgroup of data trials (solid line 1:1).*

Pourcentage de covariance entre les prévisions de la chlorphylle par satellite et la chlorophylle *in situ* classée salon le degré de corrélation (exprimé en %) entre la chlorophylle et le disque de Secchi pour chaque sous-groupe de données (trait plein 1.1).

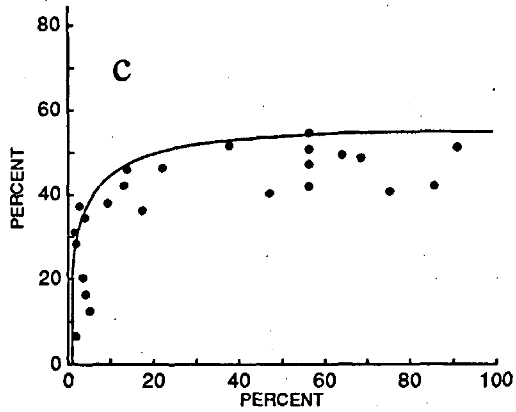

Figure 5 *c*

Percentage of covariance between satellite-derived turbidity/chlorophyll predictions and Secchi disc measurements ranked by the degree of correlation (expressed as a %) between Secchi disc and temperature for each subgroup of data trials (line indicates envelope of maximum explained data).

Pourcentage de covariance entre les prévisions de la turbiditylchlorophylle par satellite et les mesures au disque de Secchi classées selon le degré de corrélation (exprimé en %) entre le disque de Secchi et la température pour chaque sous groupe de données (le trait indique l'enveloppe du maximum de données expliquées).

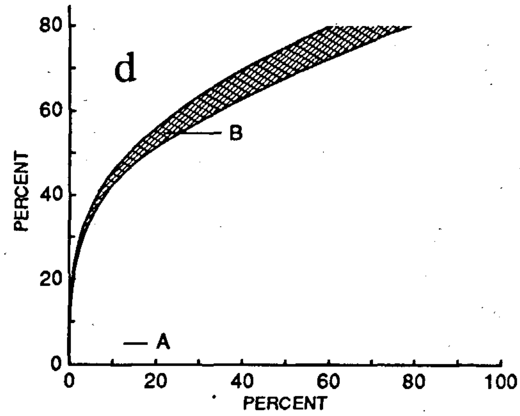

Figure 5 *d*

Mean envelope of all data analysis trails for the percentage of data retrieved (explained) from the satellite (using either chlorophyll or turbidity models) ranked against correlation pair Secchi disc with temperature and Secchi disc with chlorophyll. Shaded area gives the increase in variance retrieved from imagery using turbidity iteration schemes. A: zero time difference retrieval using all data (see text)*; B: one subset of data for a short time series of images in the summer of 1980* (see *text*).

Enveloppe moyenne de tous les essais d'analyse de données pour le pourcentage de données extraites (expliquées) du satellite (au moyen de modèles de la chlorophylle ou de la turbidité) classée en fonction de la paire de corrélation disque de Secchi c. température et disque de Secchi c. chlorophylle. La zone ombrée indique l'augmentation de la variance extraite d'images au moyen de modèles itératifs de turbidité. A : extraction avec intervalle de temps nul en utilisant toutes les données (*voir* texte) ; B : un sous-ensemble de données pour une courte série chronologique d'images à l'été 1980 (*voir* texte).

the 100 m contour along the coast and into the Gulf of Maine but left all the shallower banks in the offshore category. The inshore group was notably unimproved at all times of the year and the offshore group showed some limited/seasonal improvement by being separated from the inshore data.

Another approach is to separate the water masses by a case 1/case 2 criterion. Previous research has suggested that reflectance models can be used to provide such a separation of water types (Gordon *et al.*, 1988; Bricaud and Morel, 1987). The method adopted in this analyses is adapted from that of Bricaud and Morel (1987). The

NASA pigment algorithm was used to infer chlorophyll plus phaeophytin content, which was linked to inwater absorption and diffuse attenuation coefficients through power law relationships (Bricaud and Morel, 1987; Gordon and Morel, 1983), thereby permitting the reflectance limit at 550 nm to be calculated for case 1 waters. The station water reflectances from the CZCS data was calculated using CZCS solar constants and aerosol optical depths provided by the Miami software analysis (except when invalid aerosol optical depths were obtained in which case a value of 0.4 at all wavelengths was used). Comparison of the estimated CZCS water subsurface reflectance at 550 nm with that expected from pigment-dominated water provides a water type classification. According to this analysis 85.7 % of the CZCS samples were typed case 2. There was also no distinct geographical grouping of cases across or along the shelf for the combined data set.

The case 1/2 analysis did not "solve" the problems of image interpretation, but did assist in understanding the outcome of some of the analyses. For example, for the same day (zero day difference) analysis only 3 of the data pairs were classified as case 1. Also expanding the data selection criteria, but limiting the data to case 1, produced a maximum explained variance of only 32 % between satellite (NASA) predicted and *in situ* chlorophyll, as opposed to 11 % with Secchi disc data. With the same data selection criteria and case 2 values, explained variance was less than 9 % for both *in situ* chlorophyll and Secchi disc.

The most successful subgrouping was a combination of seasonal division of the data even when it was necessary to combine different years; regressing against water turbidity, as given by the Secchi disc depth instead of chlorophyll pigment; and using other functional forms for the satellite algorithm as suggested by Viollier and Sturm (1984). These turbidity models, whether with or without a corresponding atmospheric iterative scheme, were amongst the most successful, producing up to a 50 % increase in explained variance. This also strongly supports the case 1/2 analysis results. The quantitative elements of this subgroup are discussed in the next section.

DATA INTERPRETATION

Even for the most successful analyses data were still combined from different years and spatial parts of the shelf. To aid data interpretation a set of parameters was sought which would quantify individual data trials other than ranking them as described in the previous section. This was particularly important once more than one criterion was examined (*e.g.* offshore regions for summer data regressed against pigment under different time lag windows). The parameters selected as the "x" axes for Figures 5 *a-d* were the correlation (squared) between: 1) chlorophyll and temperature; 2) chlorophyll and Secchi disc depth; 3) Secchi disc depth and temperature; and 4) correlations (2) and (3) in Figure 5 *d*. The "y" axes in Figures 5 *a-c* represent the percentage of variance from the imagery explained by *in situ* data, each sub-figure representing different modelling assumptions. Figure 5 *a* shows that it was possible to formulate a biological interpretation of the imagery (high explained variance) when there was a strong correlation between the thermal and biological distributions. When the bio-thermal correlation was low, the ability to extract/interpret information from the imagery with a single CZCS type algorithm was also low. This "apparent" biothermal relationship is probably simply another perspective on the seasonal variation shown in Figure 2 which implies that periods of high bio-thermal correlation occurred in the spring and autumn when biological processes might be expected to dominate. Figure 5 *b* provided further support for the importance of biological dominance for interpreting imagery. When the degree of correlation between Secchi disc depth and pigment variations was high (> 60 %) the correlation between satellite predicted values and *in situ* values was also high. Once the turbidity variances no longer followed those of chlorophyll pigments, then interpretation of the imagery by use of a single bio-optical model was exceptionally poor. At these lower turbidity-pigment correlations, the Secchi disc depth was a much better index for interpreting the satellite colour data (Fig. 5 *c*), producing up to a four fold increase in explained variance for all but the lowest (< 10 %) turbidity-thermal subgroups.

If a simple two state optical system is assumed for the shelf (oceanic versus turbid), then oceanic algorithms should explain one part of the data set and turbidity algorithms (with and without corresponding atmospheric iterations) should explain another part of the data set; a combination of these results should explain a high degree of variance for all the data. In Figure 5 *d* the envelope of maximum explained variance for all models and data trial selections, regressed with either Secchi disc depth or with pigment functions, still has a region of very low interpretation of satellite imagery and hence does not support a simple oceanic-turbid seasonal and regional division of the shelf. Also at the lower correlations (low values on the "x" axes) only a marginal improvement in explained image variance was obtained when atmospheric iterations using turbidity functions were included in the atmospheric correction schemes (*see* Tab. 2).

To illustrate these inferences two of the data selections, marked A and B in Figure 5 *d*, are described in more detail below. The first (A in Fig. 5 *d*) is for a data selection of a zero time lag between *in situ* data and imagery data, which coincidentally had both low Secchi disc-thermal and low pigment-turbidity correlations; even the best model failed to explain more than 5 % of the image data probably due to the presence of multi-component optical water masses. The second group (B in Fig. 5 *d*) covered data for the summer of 1980 when a sequence of colour images indicated some evolution of perturbations along the coastal strip (*see* also Fig. 8 *c*). These features were indistinct in the corresponding cruise data which took three weeks to cover the shelf area. Maximum explained variance for this group was obtained with a continental aerosol, a ± 3 day time window and a combined oceanic and Sturm (1983) turbidity model (Sturm weighted sum, SWS, of first 4 CZCS channels) of the form:

Chlorophyll = constant x $(SWS)^{2.5}$ x $(R_{13})^{-1.8}$.

The exponent on the ratio term was determined from the multiple regression model and was the same as for the oceanic cases given by Gordon and Morel (1983), although with larger error bars. This combined model explained 48 % more variance than an oceanic model alone and could indicate that at that time the shelf contained a mixture of optically oceanic water as well as a turbidity level which co-varied with the *in situ* chlorophyll values (the case 1/2 analysis indicated that only 8 % of the data was case 1). The above model would also support the optical merging of two water masses over the few days of the perturbation rather than two distinct and separable case 1 and case 2 water masses.

LONG TERM WATER TURBIDITY

Monthly averages

Monthly composites of global ocean colour (Esias *et al.*, 1986) have shown that many global upwelling features and current systems have a colour signature associated with the seasonal biological cycle. Denman and Abbott (1988) however have noted that such image composites would be limited in their capabilities to preserve mesoscale patterns along continental margins. The satellite data was compared to the *in situ* data with a ± 14 day time lag window to obtain monthly composites for the same geographical coordinates on the shelf. The satellite imagery had been processed with a summer/winter aerosol model and the standard NASA CZCS algorithms. At this large time lag, there were only weak correlations between the monthly *in situ*/imagery data. Figure 6 shows that the monthly satellite values followed the same annual cycle as the *in situ* values of both chlorophyll and Secchi disc. The case 1/2 analysis indicated the highest proportion of case 1 samples occurred in April (Spring) whilst the lowest proportion of case 1 water, outside the winter months, occurred in August. In absolute values, the satellite pigment concentrations tended to over-estimate the *in situ* values between May and October on average by 93 % but underestimated the high spring period in April by 46 %. (Fig. 6 cannot be regarded as the annual cycle for the Scotian shelf since the spatial coverage was not consistent for each month).

Satellite data for the winter months of January and February predicted 2-4 times higher than *in situ* values; although problems have been encountered with gain 3 and 4 imagery (pers. comm. G. Feldman, NASA) this study only used gain 1 or 2 imagery. These problems are likely due to the fact that winter imagery at higher latitudes (> 45°) involves larger scattering angles for which the Rayleigh atmosphere correction algorithm in common use becomes increasingly inaccurate, having its maximum impact for the normally optically clean polar air masses (Shaw, 1982). Other local conditions have to be considered in the seasonal interpretation of colour imagery: thin ice (frazil ice, grease ice, slush) may occur off the Canadian east coast during both winter and spring months; the mean monthly air temperature off eastern Canada may seasonally be colder than the average sea temperature (*e.g.* February) and heat losses can result in near surface haze, again resulting in problems for atmospheric correction routines.

Concentration distribution

Figure 7 *a-b* gives the histogram for equal logarithmic increments of pigment concentrations for both the *in situ* data and the satellite data (processed as for the monthly analysis) for all years excluding the two anomalous winter months (January and February). Even though the data was not from a single optical water mass there was no tendency towards a bimodal distribution as had been found with the limited time series of images used by Denman and Abbott (1988). The shape of the distributions are different and the satellite peak is both higher and at a higher concentration. The case 1 concentration distributions are also included in

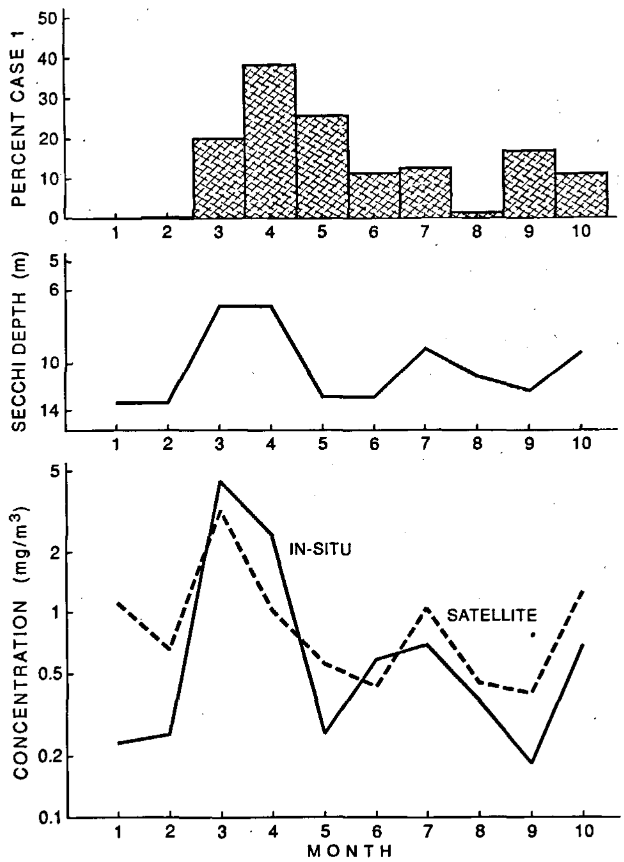

Figure 6

Monthly logarithmic average for satellite predicted chlorophyll and in situ *chlorophyll for date coincidence within the same month; Secchi disc linear average (note inverted scale); percentage case 1 data for each month.*

Moyenne logarithmique mensuelle pour la chlorophylle prévue par satellite et la chlorophylle *in situ* pour la coïncidence de date dans le même mois; moyenne linéaire de Secchi (à noter l'échelle inversée); données du cas 1 en pourcentage pour chaque mois.

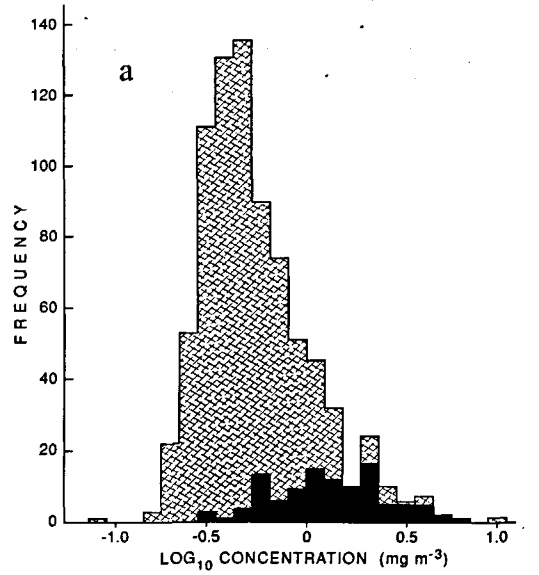

Figure 7 *a*

Concentration histogram, in logarithmic bins of 0.1, for satellite predicted pigment concentrations, shaded histogram for case I data only.

Histogramme de concentrations, par pas logarithmique de 0,1, pour les concentrations deg pigments prévus par satellite; histogramme ombré pour les données du cas 1 seulement.

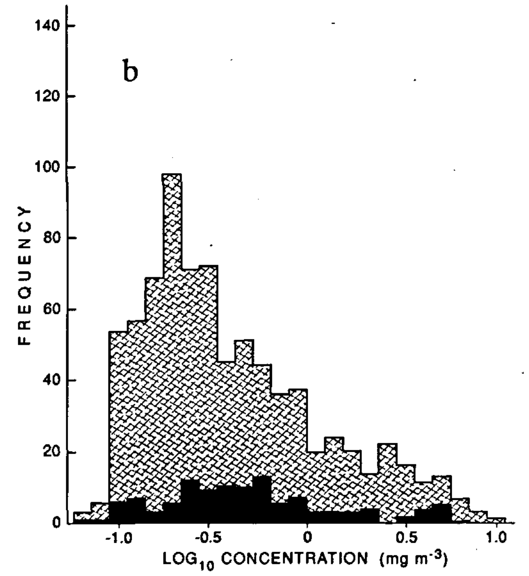

Figure 7 *b*

Concentration histogram, in logarithmic bins of 0.1, for sea truth chlorophyll concentrations, shaded histogram for case 1 data only.

Histogramme de concentrations, par pas logarithmique de 0,1, pour les concentrations de la chlorophylle contrôlée en mer; histogramme ombrée pour les données du cas 1 seulement.

Figure 7 *a-b*; again the satellite predictions are shifted towards higher concentrations relative to the *in situ* values, with distributions having no distinct concentration peaks. The addition of a concentration dependent phaeophytin component to the *in situ* chlorophyll data increased the absolute levels but made only minor changes to the distribution (Fig. 7 *b*). Conversely the value of the satellite estimates could be reduced by lowering the atmospheric (aerosol) contributions but the satellite distribution peak was still appreciably higher. At the high end of the concentration range, the *in situ* distribution was much higher than the satellite values; one assumption being that these high *in situ* pigment values were localized and inter-pixel (less than the extent of the approximately 1 km pixel). However when the *in situ* samples were split (above and below) at 1.5 mg/m^3 there was a tendency for the corresponding satellite distributions to retain the same median value; this again indicated that the low concentrations were over predicted whereas the high concentrations were under predicted as the CZCS algorithms attempted to interpret turbidity levels as oceanic biological pigments.

OCEAN FEATURES AND VISIBLE IMAGERY

Most of the satellite data was not correlated with "open ocean chlorophyll" predictions except for the longer term underlying biological cycle. This cycle controlled the turbidity level which in turn allowed these levels to be monitored by the CZCS sensors. Features observed in the images were more likely to be biologically co-varying material with an unknown sediment or detrital component. Similarly colour features associated with any thermal features were not necessarily of biological origin. Outside the spring bloom period there was a 4:1 probability that the information content of the imagery was related to general turbidity rather than pigments.

Particular colour features in the imagery were compared to potentially corresponding thermal features and corresponding current systems found on the Scotian shelf (*see* Fig. 1 and "Introduction"). Figure 8 *a* shows an area off south-west Nova Scotia where the colour front followed the bathymetric contours in a similar manner to known thermal studies. The "colour" on the shore side of the front was likely to have a large terrestrial and sedimentary constituent with the highest values occurring further into the Bay of Fundy, an area of extremely high tidally resuspended sediments. Along the Nova Scotia coast, a narrow band of colour, Figure 8 *b*, within the 100 m contour, occurred for a considerable part of the year. Given the earlier offshore/onshore analysis (also *see* Topliss, 1982 *b*), this band was unlikely to be dominated by pigments for most of the time and can only be assumed to be influenced by land drainage and nearshore wind turbulence with no obvious thermal comparison. However during a short period in the summer of 1980 this band increased and showed some signs of instability (*see* Fig. 8 *c*), which merged with shelf water (*see* "Data interpretation" section, and B in Fig. 5 *d*). Finally there was at least one occurrence in the colour imagery (Fig. 8 *d*) in the late summer of evidence of a distinct colour surface feature emerging out of the Gulf of St. Lawrence along the Laurentian Channel to the shelf edge where it showed possible signs of a hammerhead-like instability at the shelf break. This burst of surface colour also showed

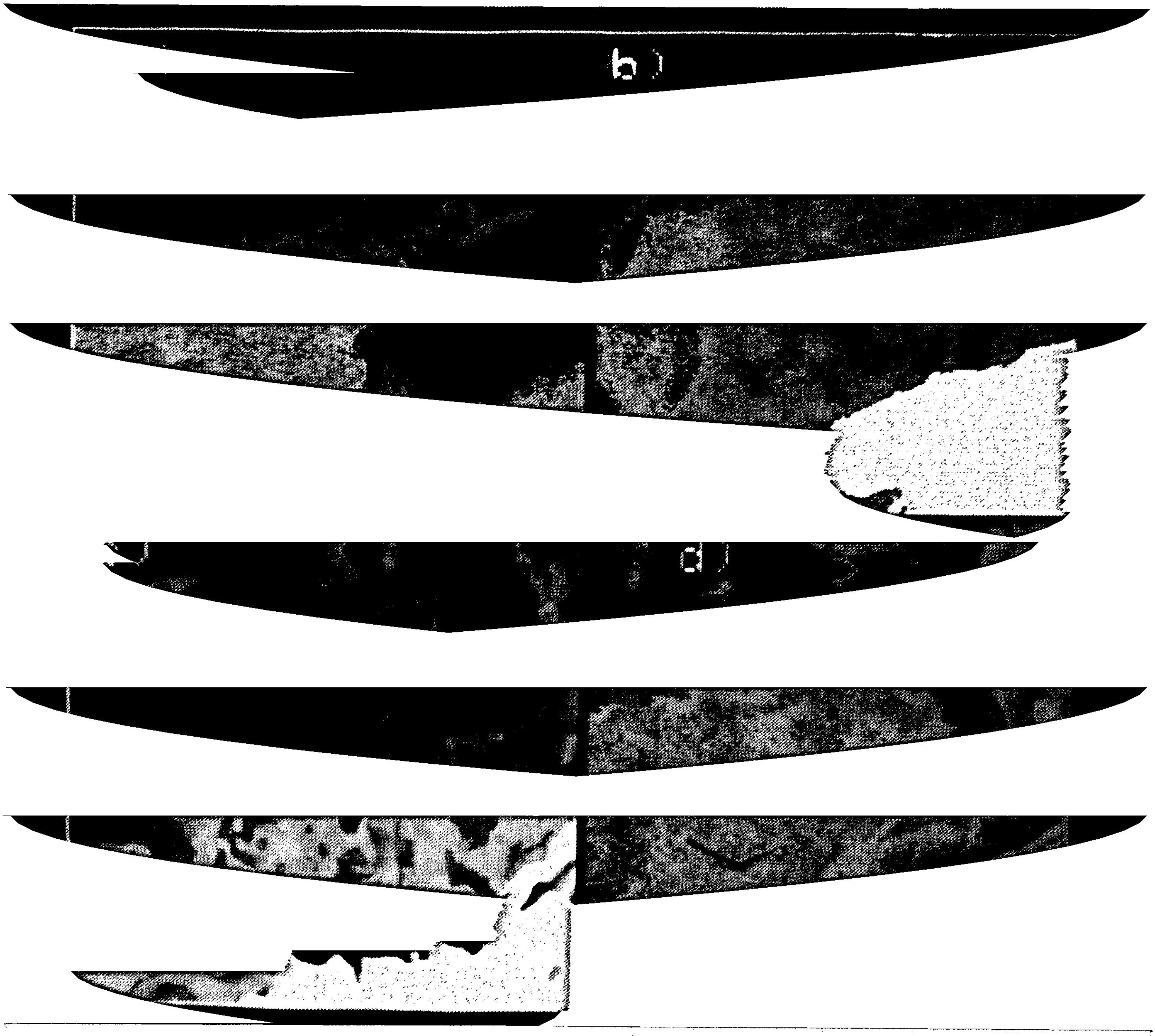

Figure 8

Colour features: a) following the bathymetric features around the southwestern coast of Nova Scotia (April 1979); b) narrow turbidity band along coast of Nova Scotia (June 1979); c) merging of coastal band with offshore shelf waters (June 1980); d) surface turbidity feature associated with outflow of Gulf of St. Lawrence (August 1979).

Éléments en couleur : a) suivant les éléments bathymétriques autour de la côte sud-ouest de la Nouvelle-Écosse (avril 1979) ; b) zone étroite de turbidité le long de la côte de la Nouvelle-Écosse (juin 1979) ; c) fusion d'une zone côtière avec les eaux de la plate-forme au large (juin 1980) ; d) élément de turbidité superficielle associé à la circulation sortant du fleuve St-Laurent (août 1979).

marked fine structures, including numerous swirls, in the 670 nm water extractions. Imagery from several years from the Gulf of St. Lawrence end of the shelf was found to have high "colour" levels in late summer (August to early October) which could spread along the coast, that is down the shelf, but in a less defined manner compared to Figure 8 *d*. In the earlier *in situ*/imagery analyses these elevated colour regions were optimized by algorithms with R_{23} ratio combinations indicating both potential high levels of chlorophyll and/or eroded blue wavelength signal. The case 1/2 analysis also indicated the August data as having the highest component of case 2 (non-oceanic) water. Drinkwater and Trites (1987) showed a seasonal outflow of low (< 29) salinity water from the Gulf of St. Lawrence which would be associated with fresher water and likely higher dissolved organic content all contributing to reduced blue signals. The lowest salinity water however occurred typically in Sepembert/October which was later than the August "colour burst" shown in Figure 8 *d*.

CONCLUSIONS

In summary the relatively limited amount of colour imagery examined in this study revealed:

1) Colour imagery highlighted processes on the shelf probably to the same extent as infrared imagery. The only exception was the narrow nearshore turbid layer, also sometimes visible from ships heading out of Halifax harbour, which had no known thermal analogy.

2) A single bio-optical model did not explain most of the imagery; a turbidity index, such as Secchi disc depth, together with satellite turbidity models were more efficient in explaining the colour patterns on the shelf, consistent with the calculations that estimated 86 % of the sample points were case 2 waters. However, with sufficient spatial and temporal averaging on the shelf the only remaining variation was the biologically dominated annual cycle. In such a situation the imagery, averaged in a similar manner, when processed with a single bio-optical model could provide interpretation of long term spatial biological processes but would not be expected to provide valid inferences on inter-annual variability.

3) Since most of the Scotian shelf water was deduced not to be case 1 (oceanic), then all the colour features observed provided some information on the behaviour of the local water mass. In some cases freshwater runoff was believed to influence data, in other cases influences were general terrestrial dissolved material or resuspended sediments. Although quantitative values could not be fixed to the colour signals in each image, the multi-component systems influencing marine environmental colour were evident and indicated considerable potential for understanding shelf processes with future and more advanced remote colour monitoring and modelling.

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REFERENCES

Abbott M.R. and P.M. Zion (1985). Satellite observations of phytoplankton variability during an upwelling event. *Continent. Shelf Res.*, **4**, 6, 661-680.

Austin R.W. and T.J. Petzold (1980). The determination of the diffuse attenuation coefficient of sea water using the coastal zone color scanner. In: *Oceanography from Space*, J.F.R. Gower, editor, Plenum Press, New York, 239-256.

Balch W.M., R.W. Eppley, M.R. Abbott and F.M.H. Reid (1989). Bias in satellite derived pigment measurements due to coccolithophores and dinoflagellates. *J. Plankt. Res.*, **11**, 3, 575-581.

Bricaud A. and A. Morel (1987). Atmospheric corrections and interpretation of marine radiances in CZCS imagery: use of a reflectance model. *Actes du Colloque "Océanographie spatiale", Brest, France, 19-20 novembre 1985, Oceanologica Acta.* **vol. sp. n° 7**, 33-50.

Brown O.B., R.H. Evans, J.W. Brown, H.R. Gordon, R.C. Smith and K.S. Baker (1985). Phytoplankton blooming of the US east coast: a satellite description. *Science*, **229**, 163-167.

Denman K.L. and M.R. Abbott (1988). Time evolution of surface chlorophyll patterns from cross-spectrum analysis of satellite color images. *J. geophys. Res.*, **93**, C6, 6789-6798.

Drinkwater K.F. and R.W. Trites (1987). Monthly means of temperature and salinity in the Scotian Shelf region. Canadian Technical Report of Fisheries and Aquatic Sciences n° 1539, 101 pp.

Drinkwater K., B. Petrie and W.H. Sutcliffe Jr. (1979). Seasonal geostrophic volume transports along the Scotian Shelf. *Estuar. coast. mar. Sci.*, **9**, 17-27.

Esias W.E., G.C. Feldman, C.R. McClain and J.A. Eldrod (1986). Monthly satellite-derived phytoplankton pigment distribution for the North Atlantic Ocean basin. *Eos*, **67**, 44, 835-837.

Fournier R.O., J. Mara, R. Bohrer and M. van Det (1977). Plankton dynamics and nutrient enrichment of the Scotian Shelf. *J. Fish. Res. Bd Can.*, **34**, 1004-1018.

Garrett C.J.R. and R. Loucks (1976). Upwelling along the Yarmouth shore of Nova Scotia. *J. Fish. Res. Bd Can.*, **33**, 116-117.

Gordon H.R. (1978). Removal of atmospheric effects from satellite imagery of the oceans. *Appl. Opt.*, **17**, 1631-1636.

Gordon H.R. and A.W. Wouters (1978). Some relationships between Secchi depth and inherent optical properties of natural waters. *Appl. Opt.*, **17**, 21, 3341-3343.

Gordon H.R. and D.K. Clark (1981). Clear water radiances for atmospheric correction of coastal zone color scanner imagery. *Appl. Opt.*, **20**, 4175-4180.

Gordon H.R. and A.Y. Morel (1983). *Remote Assessment of Ocean Color for Interpretation of Satellite Visible Imagery: a Review.* Springer-Verlag, New York, 114 pp.

Gordon H.R. and D.J. Castano (1987). The coastal zone color scanner atmospheric correction algorithm: multiple scattering effects. *Appl. Opt.*, **26**, 2111-2122.

Gordon H.R. and R.H. Evans (1990). The CZCS: algorithms and characterization; presented at *Venice, 1990, Oceans from Space, Venice, Italy, May 22-26.*

Gordon H.R., O.B. Brown, R.H. Evans and D.K. Clark (1983). Nimbus-7 CZCS: reduction of its radiometric sensitivity with time, *Appl. Opt.*, **22**, 24, 3929-3931.

Gordon H.R., O.B. Brown, R.H. Evans, J.W. Brown, R.C. Smith, K.S. Baker and D.K. Clark (1988). A semianalytic model of ocean color. *J. geophys. Res.*, **93**, D9, 10909-10924.

Hobson L.A., D.W. Menzel and R.T. Barber (1973). Primary productivity and the sizes of pools of organic carbon in the mixed layer of the ocean. *Mar. Biol.*, **19**, 298-306.

Holligan P.M., M. Viollier, D.S. Harbour, P. Camus and M. Champagne-Philippe (1983). Satellite and ship studies of Coccolithophore production along a continental shelf edge. *Nature*, **304**, 339-342.

Holmes R.W. (1970). The Secchi disk in turbid coastal waters. *Limnol. Oceanogr.*, **15**, 5, 688-694.

Horne E.P.W. (1978). Interleaving at the subsurface front in the slope water off Nova Scotia. *J. geophys. Res.*, **83**, 3659-3671.

Houghton R.W., P.C. Smith and R.O. Fournier (1978). A simple model for cross-shelf mixing on the Scotian Shelf. *J. Fish. Res.Bd Can.*, **35**, 414-421.

Johnston R.J. (1978). *Multivariate Statistical Analysis in Geography*. Longman, 280 pp.

Le Bouteiller A. and A. Herbland (1982). Diel variation of chlorophyll a as evidenced from a 13-day station in the equatorial Atlantic Ocean. *Oceanologica Acta*, **5**, 4, 433-441.

McClatchey R.A., R.W. Fenn, J.E.A. Selby, F.E. Volz and J.S. Gaving (1972). Optical Properties of the Atmosphere. 3rd ed.. AFCRL-72-0497, 24 August 1972, Environmental Research Papers n° 411.

McLellan H.J. (1957). On the distinctness and origin of the slope waters off the Scotian Shelf and its easterly flow south of the Grand Banks. *J. Fish. Res. Bd Can.*, **14**, 213-239.

Mills E.L. and R.O. Fournier (1979). Fish production and the marine ecosystem of the Scotian Shelf, Eastern Canada. *Mar. Biol.*, **54**, 101-108.

Mitchelson E.G., N.J. Jacob and J.H. Simpson (1986). Ocean colour algorithms from Case 2 waters of the Irish Sea in comparison to algorithms from Case 1 waters. *Continent. Shelf Res.*, **5**, 3, 403-415.

Morel A. and L. Prieur (1977). Analysis of variations in ocean color. *Limnol. Oceanogr.*, **22**, 4, 709-722.

Mueller J.L. (1985). Nimbus-7 CZCS: confirmation of its radiometric sensitivity decay through 1982. *Appl. Opt.*, **24**, 7, 1043-1047.

Neckel H. and D. Labs (1981). Improved data of solar spectral irradiance from 0.33 to 1.25 µm. *Solar Phys.*, **74**, 231-249.

Neckel H. and D. Labs (1984). The solar radiation between 3300 and 12500A°. *Solar Phys.*, **90**, 205-258.

O'Boyle R.N., M. Sinclair, R.J. Conover, K.H. Mann and A.C. Kohler (1984). Temporal and spatial distribution of ichthyoplankton communities of the Scotian Shelf in relation to biological, hydrological, and physiographic features. *Rapp. P-v. Réun. Cons. perm. int. Explor. Mer*, **183**, 27-40.

Petrie B. (1987). Undulations of the Nova Scotia Current. *Atmos. Ocean*, **25**, 1, 1-9.

Petrie B. and P.C. Smith (1979). Low-frequency motions on the Scotian Shelf and Slope. *Atmosphere*, **15**, 117-140.

Petrie B., B.J. Topliss and D.G. Wright (1987). Coast upwelling and eddy development off Nova Scotia. *J. geophys. Res.*, **29**, C12, 12979-12991.

Postma H. and D. Spitzer (1982). Possible daily variation in the color of the blue ocean. *Appl. Opt.*, **21**, 1, 12-14.

Preisendorfer R.W. (1986). Secchi disk science: visual optics of natural waters. *Limnol. Oceanogr.*, **31**, 5, 909-926.

Prieur L. and S. Santhyendranath (1981). An optical classification of coastal and oceanic waters based on the specific absorption curves of phytoplankton pigments, dissolved organic matter, and other particulate materials. *Limnol. Oceanogr.*, **26**, 671-689.

Robinson I.S. (1985). *Satellite Oceanography. An Introduction for Oceanographers and Remote-sensing scientists*. Ellis Horwood, 455 pp.

Ryther J.H., D.W. Menzel and R.F. Vaccaro (1961). Diurnal Variations in the chemical and biological properties of the Sargasso Sea. *Limnol. Oceanogr.*, **6**, 149-153.

Shaw G.E. (1982). Atmospheric turbidity in the polar regions. *J. appl. Met.*, **21**, 1080-1088.

Simpson J.H. and J. Brown (1987). The interpretation of visible band imagery of turbid shallow seas in terms of the distribution of suspended particulates. *Continent. Shelf Res.*, **7**, 11/12, 1307-1313.

Smith P.C. (1983). The mean and seasonal circulation off southwest Nova Scotia. *J. Phys. Oceanogr.*, **13**, 1034-1054.

Smith R.C. and K.S. Baker (1978). Optical classification of natural waters. *Limnol. Oceanogr.*, **23**, 260-279.

Smith R.C. and K.S. Baker (1982). Oceanic chlorophyll concentrations as determined by satellite (Nimbus 7 coastal zone color scanner). *Mar. Biol.*, **66**, 269-279.

Smith P.C. and B.D. Petrie (1982). Low-frequency Circulation at the Edge of the Scotian Shelf. *J. phys. Oceanogr.*, **12**, 1, 28-46.

Smith P.C., B. Petrie and C.R. Mann (1978). Circulation, variability and dynamics on the Scotian Shelf and Slope. *J. Fish. Res. Bd Can.*, **35**, 1067-1083.

Sturm B. (1981). Ocean color remote sensing and retrieval of surface chlorophyll in coastal waters using the Nimbus-7 CZCS in: *Oceanography from Space*. J.F.R. Gower, editor, Plenum Press, New York, 267-280.

Sturm B. (1983). Selected topics of Coastal Zone Color Scanner (CZCS) data evaluation, in: *Remote Sensing Applications in Marine Science and Technology*. A.P. Cracknell, editor, Reidel Publishing Company, 137-167.

Sutcliffe Jr., W.H., R. Louchs and K. Drinkwater (1976). Coastal circulation and physical oceanography of the Scotian Shelf and Gulf of Maine. *J. Fish. Res. Bd Can.*, **33**, 98-115.

Topliss B.J. (1982 *a*). Optical monitoring of coastal waters: photic depth estimates. *Mar. environ. Res.*, **7**, 4, 295-308.

Topliss B.J. (1982 *b*). Water colour in eastern canadian inshore areas. *NAFO Science Council Studies, Special Session on remote sensing. September 1981*, **4**, 63-67.

Topliss B.J. (1989). Ocean Colour Imagery: An investigation of some water related parameters influencing algorithm development and data product interpretation. *Can. J. Remote Sens.*, **15**, 1, 56-67.

Topliss B.J., L. Payzant and P.C.F. Hurley (1988). Monitoring off-shore water quality from space. *Proceedings of IGARSS'88 Symposium, Edinburgh, Scotland, 13-16 September 1988, Vol III*, 1399-1402.

Topliss B.J., J.R. Miller and B. Irwin (1989 *a*). Ocean optical measurements. I: Statistical analysis of data from the western North Atlantic. *Continent. Shelf Res.*, **9**, 113-131.

Topliss B.J., J.R. Miller and E.P.W. Horne (1989 *b*). Ocean optical measurements. II: Statistical analysis of data from Canadian eastern Arctic waters. *Continent. Shelf Res.*, **9**, 133-152.

Tyler J.E. (1968). The Secchi Disc. *Limnol. Oceanogr.*, **13**, 1, 1-6.

Vigroux E. (1953). Contribution à l'étude expérimentale de l'absorption de l'ozone. *Ann. Phys.*, **8**, 709-762.

Viollier M. (1982). Radiance calibration of the coastal zone color scanner: a proposed adjustment. *Appl. Opt.*, **21**, 1142-1145.

Viollier M. and B. Sturm (1984). CZCS data analysis in turbid coastal water. *J. geophys. Res.*, **89**, D4, 4977-4985.