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OPTICAL PROPERTIES OF INLAND WATERS: AN ESSENTIAL REQUIREMENT FOR MONITORING NATURAL AND ANTHROPOGENIC CLIMATE CHANGES FROM SPACE

by

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ABSTRACT

A major objective of both the International Geosphere-Biosphere Program (IGBP) and the Global Change: Impact on Habitability (GCIH) is an ecosystematic study of the increased anthropogenic impact on the evolution of the earth's geosphere and biosphere. The oceanology aspect of such satellite-based ecosystematic approaches is discussed, and the importance of being able to reliably monitor chlorophyll concentrations in optically complex inland as well as oceanic water masses is emphasized. Methodology is presented from which water quality parameters (concentrations of chlorophyll, suspended mineral, dissolved organic carbon and non-living organics) may be estimated from directly measured or inferred subsurface irradiance reflectance (volume reflectance) spectra. The direct linkages between volume reflectance and water quality parameters are the optical cross sections (absorption and scattering per unit concentration of principal aquatic components), and a strong recommendation is made that such optical cross sections be determined for principal water bodies on a global scale. This strong recommendation is promoted despite the variabilities displayed by the chlorophyll cross sections. The optical properties of chlorophyll are species, time and space dependent. They may also be a function of the very climate changes they are being used to monitor. Two sets of chlorophyll absorption cross section spectra obtained for Lake Ontario are presented and the discrepancies between these two sets of spectra as well as discrepancies among absorption spectra obtained by other workers are illustrated and discussed.

RÉSUMÉ

L'étude écosystématique des répercussions accrues des interventions humaines sur l'évolution de la géosphère et la biosphère de notre planète constitue un objectif majeur du programme international Géosphère-Biosphère (PIGB) et du programme Changement global : effets sur l'habitabilité (GCIH). Il est question ici du volet océanologique de telles méthodologies d'étude écosystématique par satellite. On insiste sur l'importance d'être en mesure de contrôler de manière fiable la concentration en chlorophylle à l'intérieur de masses d'eau océaniques aussi bien qu'intérieures qui sont complexes sur le plan des analyses optiques. On présente des méthodologies permettant l'évaluation de paramètres de la qualité de l'eau (concentration en chlorophylle, matières minérales en suspension, carbone organique dissous et matières organiques non vivantes), à partir de spectres déduits ou mesurés directement d'éclairement interne (diffus) ou de réflexion (réflectance volumique) sous la surface d'un plan d'eau. Les sections optiques constituent les liens directs entre la réflectance volumique et les paramètres de qualité de l'eau (absorption et diffusion par unité de concentration des principaux composants aquatiques); il est vivement recommandé de déterminer ces sections optiques dans les principaux plans d'eau à l'échelle mondiale. Cette vive recommandation est avancée malgré la variabilité des sections associées à la chlorophylle. Les propriétés optiques de la chlorophylle sont fonction des espèces, du moment et de l'emplacement. Elles peuvent également être en fonction des changements climatiques mêmes qu'on tente de suivre. Deux ensembles

de spectres de section d'absorption associés à la chlorophylle ont été obtenus dans le lac Ontario; ils sont présentés et les discordances entre les deux ensembles de spectres ainsi que celles entre ceux-ci et les spectres d'absorption obtenus par d'autres chercheurs, sont illustrées et analysées.

MANAGEMENT PERSPECTIVE

An historically unprecedented volume of anthropogenic loadings have impacted the earth's environment. This ever-increasing anthropogenic impact, superimposed upon natural impacts (both passive and proactive) have resulted in an intensified evolution of the geosphere and biosphere. An obvious and global consequence of such natural and man-made influences (continuous and/or catastrophic) is a disruption of the natural evolution of near-surface temperatures. Such temperature disruptions will manifest as anthropogenically-induced climatic changes superimposed upon and interacting with naturally occurring climatic changes. The abilities to both monitor and predict such natural and anthropogenic climate changes must be both defined and devised. At this moment in time, such abilities, while appreciated, do not exist in sufficiently reliable or reproducible form to be directly applied to the complex interactive ecosystems comprising the entirety of the solar/terrestrial environment.

To obtain such abilities, multidisciplinary ecosystem studies of the geosphere and biosphere are required. Global participation and satellite monitoring systems are requisites for the successful implementation of such large scale and complex environmental pursuits. These circumstances have stimulated the development of a long-term International Geosphere-Biosphere Program (IGBP) initiated at a National Research Council Workshop at Woods Hole in 1983, and officially endorsed by the International Council of Scientific Unions in 1986. The observation platform is scheduled for launch in the 1990's. Independent of this global program (under the aegis of SCOPE, UNEP, UNESCO, etc.) is the NASA program Global Change: Impact on Habitability (GCIH). Both IGBP and GCIH are dedicated towards an unravelling of the feedback-loop couplings of the terrestrial and inner solar cavity environments.

That the planetary aquatic resources play a major role in such global climatology studies is undeniable. Both as a means of monitoring global climate change and contributing to the development of predictive/interpretive climate change models, the capability of measuring water quality from space is essential. The Environmental Spectro-Optics Group at NWRI has, over the years, developed models and optical methodologies which enable remote estimates of chlorophyll, suspended mineral, and dissolved organic carbon concentrations to be performed once reliable subsurface volume reflectance spectra are directly measured or remotely inferred. The direct linkages between remote determinations of water quality and subsurface volume reflectances are the individual optical cross sections of each component of the water mass being remotely monitored. These optical cross sections are defined as the specific amount of absorption and the specific amount of scattering at each wavelength attributable to one unit of concentration of each of the components.

This manuscript describes how such optical cross sections may be obtained through a combined theoretical/field study involving the use of optical models, regression and/or optimization analyses, direct or remote measurements of subsurface volume reflectance and the collection and analyses of water quality samples.

The manuscript discusses the complexities of such optical cross section determinations and how such cross sections (particularly for chlorophyll) are functions of species of chlorophyll-bearing biota, growth cycle of such biota, and perhaps, through a complex bioenvironmental feedback loop, a function of the very climate changes they are being used to monitor. These difficulties notwithstanding, however, a strong recommendation is made that global cooperation be implemented in obtaining such aquatic cross sections for each major water body if the goals and aims of IGBP and GCIH are to be reached.

PERSPECTIVE-GESTION

Un volume sans précédent de produits d'origine anthropique est apparu dans l'environnement mondial. Cet effet anthropique sans cesse croissant, qui est superposé à des effets naturels (passifs et actifs) a intensifié l'évolution de la géosphère et de la biosphère. La perturbation de l'évolution naturelle des températures à proximité de la surface constitue l'une des conséquences évidentes et mondiales de telles influences (exercées de manière continuelle ou de manière catastrophique). Pareilles perturbations thermiques sont manifestées sous la forme de modifications climatiques d'origine anthropique qui se superposent à des changements climatiques naturels et entrent en interaction avec ceux-ci. Il importe de définir les moyens de contrôler et de prévoir ces changements climatiques naturels et anthropiques et de mettre au point les méthodologies correspondantes. À ce jour, ces moyens, quoique appréciés, n'ont pas une fiabilité ou une reproductibilité suffisante pour être appliqués directement à des écosystèmes interactifs complexes qui portent sur l'ensemble de l'environnement terrestre et de l'environnement solaire.

La mise au point de ces moyens nécessite la tenue d'études écosystématiques multidisciplinaires qui portent sur la géosphère et la biosphère. Une participation mondiale et le recours à la surveillance par satellite sont des prérequis pour la réalisation de ce genre d'études écologiques complexes et à grande échelle. Ces circonstances ont favorisé l'élaboration d'un programme d'étude de la géosphère et de la biosphère de grande durée (PIGB) qui a été lancé à l'atelier du Conseil national de recherche à Woods Hole en 1983 et qui a été endossé officiellement par le Conseil international des unions scientifiques en 1986. La plate-forme d'observation doit être lancée au cours des années 1990. Le programme de la NASA, Global Change : Impact on Habitability (GCIH), est un programme indépendant du programme mondial précédent (sous l'égide du CSPE, du PNUE, de l'UNESCO, etc.). Les deux programmes ont pour objectif la compréhension des couplages par boucle de rétroaction de l'environnement terrestre et de l'environnement solaire dans le périmètre des planètes.

Il ne fait aucun doute que les ressources aquatiques planétaires occupent une place importante dans les études climatologiques mondiales. La capacité de mesurer la qualité de l'eau à partir de l'espace est essentielle, tant comme moyen de contrôler le changement climatique mondial que comme moyen de contribuer à l'élaboration de modèles d'interprétation et de prévision des changements climatiques. Le groupe de spectro-optique environnementale de l'INRE a mis au point, au cours des ans, des modèles et des méthodologies optiques qui permettent de procéder à des évaluations de la concentration en chlorophylle, en minéraux en suspension et en carbone organique dissous une fois que des spectres de réflectance volumique subsuperficielle ont été directement mesurés ou déduits à partir d'observations à distance. Les sections optiques individuelles de chaque composant de la masse d'eau contrôlée à distance constituent les interfaces directes entre les déterminations à distance de la qualité de l'eau et les réflectances volumiques subsuperficielles.

Ces sections optiques sont définies de la façon suivante : le niveau spécifique d'absorption et le niveau spécifique de diffusion de la lumière à chaque longueur d'onde qui sont attribuables à une unité de concentration de chacun des composants considérés.

Ce rapport manuscrit décrit comment de telles sections optiques peuvent être obtenues après une étude qui comporte un volet théorique et un volet sur le terrain et qui fait intervenir des modèles optiques, des analyses d'optimisation ou de régression, des mesures directes ou à distance de la réflectance volumique subsuperficielle et la cueillette et l'analyse d'échantillons pour la qualité de l'eau.

Ce rapport manuscrit analyse les complexités associées à la détermination de ces sections optiques et comment ces sections (notamment celles de la chlorophylle) varient en fonction des espèces qui constituent les biotes qui contiennent la chlorophylle, du cycle de croissance de ces biotes et, peut-être, par l'intermédiaire d'une boucle de rétroaction bioenvironnementale complexe, sont-elles aussi en fonction des changements climatiques mêmes qu'elles servent à contrôler. Peu importe cette difficulté, il est fortement recommandé d'engager une coopération mondiale afin que soient déterminées ces sections dans chaque plan d'eau important si on compte atteindre les buts et objectifs donnés au PIGB et au GCIH.

INTRODUCTION

The need to apply realistically practical ecosystematic studies to the solar/terrestrial environment has been dramatically underscored in recent years by the growing realization that climatic variations significantly impact mankind's economic activities. Further, with the ever-increasing economic participation of the populace on a global scale, such economic activities are adding an unprecedented anthropogenic influence to the evolution of the biosphere and geosphere. The interactive nature of the interdisciplinary components of the biosphere and geosphere, coupled with the complexity of the laws governing their interactions, necessitates immediate improvements to existing climate models, weather and climate forecasting techniques, and parametric monitoring activities on a global scale. Particular emphasis needs to be directed towards both the monitoring and analyses of observed irregularities in climatic change caused by unambiguously relatable and accurately measurable (or predictable) anthropogenic environmental loadings as well as naturally-occurring (separate from anthropogenic) climatic changes whose cause/effect relationships are still not fully understood (see, for example, the excellent discussions presented by Kondratyev, 1987; 1988; Munn, 1988; Izrael, 1984; Schlesinger, 1984; Crutzen and Gidel, 1983; Ellsaesser, 1985; National Academy of Sciences, 1983). For example, as described in Kelly et al. (1985) for the case of estimations of the mean annual near-surface air temperatures (NSAT), serious contradictions among existing and developing estimation techniques must be resolved in a scientifically satisfactory manner. This example of contradictions in NSAT estimations illustrates a particularly crucial aspect of climate change methodology since long term warming and/or cooling trends, upon which are superimposed short term, possibly catastrophic, thermal impacts (volcanic eruptions, solar activity cycles, nuclear tests, warfare, etc.), provide the most singularly important consideration for evaluating natural and/or anthropogenic influences on global climate.

Clearly, therefore, complex multidisciplinary environmental programs designed to monitor and interpret climatic changes in terms of an ecosystematic approach to solar/terrestrial relationships are essential for environmental survival. Such large scale environmental programs are not without successful precedent. Examples include the International Geophysical Year (IGY), the International Quiet Sun Year (IQSY), the Global Atmospheric Research Program (GARP) and the recent World Climate Program (WCP). In addition, there are the initiatives of specialty programs such as the International Satellite Cloud Climatology Project (ISCCP), the World Ocean Circulation Experiment (WOCE) and the Tropical Ocean and Global Atmosphere Program (TOGA). One common feature uniting all the above global participation programs was (and is) the integral role played in such worldwide dramas by earth-orbiting satellites and/or deep-space probes, due, in large part to the facts that:

(a) Solar/terrestrial relationships are dictated by the wavelength-dependent radiative transfer mechanisms interrelating solar and galactic radiation, solar and terrestrial magnetic fields and plasmas, and the chemical, physical, and biological components of the terrestrial atmosphere and biosphere. Consequently, the physical principles of spectro-optics comprise a major component of any global program concerned with climatic change occurring within the inner solar cavity. *In situ* measurements of spectro-optical parameters are, of course, central to such a scientific component even during periods of minimum solar activity (McCracken *et al*., 1967).

(b) The increasing anthropogenic impact on the global geosphere (manifested, in part, as an impact on the carbon and nitrogen cycles through excessive concentrations of carbon dioxide and nitrogen oxides) necessitates the capability of synoptically observing global-scale processes and changes occurring within the atmosphere, ocean, cryosphere, and lithosphere in addition to extra-terrestrial radiations and magnetic field strengths.

FACTORS DETERMINING CLIMATIC CHANGES

Perhaps the single most important factor determining climatic change is the observed variability (both in space and time) of the near-surface air temperature (NSAT). A myriad of factors, however, are inter-involved in the generation of NSAT variability. These factors include such external forces as large-scale volcanic eruptions and increased carbon dioxide concentrations, such external oscillation factors as solar sunspot cycle and lunar tidal cycles, such internal oscillation factors as the El Nino/South Oscillation phenomenon (ENSO), and such chance process factors as determined by the dynamic instability of the atmosphere. Much valuable literature exists concerning climatic change, NSAT, and various feedback links (i.e., transfer of sensitive and latent heat between ocean and atmosphere including albedo effects of ice, clouds, etc.) and includes, amongst many others, the works by Holland *et al*. (1986); Roeckner *et al*. (1987); Woods (1985) U.S. Environmental Protection Agency (1984); Stone (1984); Khalil and Rasmussen (1988); National Academy of Sciences (1983); Tucker *et al*. (1986); Twomey *et al*. (1984); Ellsaesser (1985); Kelly *et al*. (1985); Gutowski *et al*. (1985); and other authors appearing in American Meteorological Society (1985). Much also has been written on the possible scenarios arising from post-war "nuclear winter", the greenhouse effect, and the erosion of the ozone layer. It would be extremely presumptuous to suggest that this communication presents an experimental protocol for solving the monumentally complex problems of monitoring and analyzing natural and anthropogenic climate changes as determined from space-borne optical instrumentation. It is extremely less presumptuous, however, to concentrate on one aspect of the soon-to-be-implemented International Geosphere-Biosphere Programme (IGBP) and suggest that the role of the Earth's aquatic resources in both actively modulating and passively responding to global climatic changes, may be far better understood if the optical properties of both inland and oceanic water masses be monitored as a function of both space and time.

THE OCEANOLOGY ASPECT OF IGBP

A coordinated long-term International Geosphere-Biosphere Programme (IGBP), endorsed and initiated by the International Council of Scientific Unions, with the launching of a space observation station scheduled in the early 1990's, is intended to study global climatic changes (National Research Council, 1983) on timescales of decades to centuries. In addition, the independent, but closely related NASA program Global Change: Impact on Habitability (GCIH) is being developed (NASA, 1982; 1983). Of particular concern to both IGBP and GCIH is the anthropogenic impact on the biogeochemical cycles of carbon, nitrogen, sulfur, phosphorus, and water, in addition to such environmental health indicators as solar radiation, water quality, air quality, and soil fertility. Regarding the remote sensing of environmental parameters from space, the IGBP strategy is to divide environmental problems into the general categories agriculture, forestry, geology, hydrology, and oceanology. Within the category of oceanology, specific problems include:

(a) Sea surface state
(b) Sea ice

(c) Aquatic turbidity

(d) Coastal tides and currents

(e) Global-scale currents and sea surface state

(f) Distribution and migration of aquatic organisms

(g) Coastal aquatic contamination

(h) Near-shore processes

(i) Bathymetry and topography of ice

(j) Coastline mapping

(k) Bars, reefs, shoals, etc.

(l) Shallow water bathymetry

Clearly, an important priority issue to the assessment and predictability of global climatic change is the ability to i) determine and record changes in the inputs of the biogenic components (nitrogen, sulfur, phosphorus) as well as toxic rain, heavy metal, and oxidant depositions, ii) the impact of such biogenic changes on carbon reservoirs, iii) the reaction of biota to climatic changes, and iv) the carbon ratio between living and non-living components of such carbon reservoirs. Therefore, the problem of biological productivity on land and water is an important priority issue. For the case of water, biological productivity assessment requires reliable information concerning biogenic input fluxes driven by groundwater flow pathways and riverine transport to large lakes and oceanic coastal zones and ultimately to great depths in oceans. The role of the atmosphere in transporting biogenic inputs from land to water is also of prime importance to aquatic bioproductivity, in addition, of course, to the impinging solar radiation fluxes. Equally important to the overall assessment of aquatic productivity is the ability to accurately monitor from space a measure of such aquatic productivity while simultaneously monitoring the quality of the water in which such production is (or isn't) occurring as a function of both space and time. This requires the ability to distinguish at any given time and/or place the principal organic and/or inorganic components, in particular the chlorophyll and suspended mineral concentrations, characterizing the water body being remotely sensed.

ESTIMATING WATER QUALITY FROM SPACE

Elsewhere (Bukata et al., 1981; 1985) we have detailed the methodology by which direct measurements of the subsurface apparent optical properties subsurface irradiance reflectance (volume reflectance) R and the irradiance attenuation coefficient k (both as functions of the visible wavelength λ and depth Z) and the inherent optical property total attenuation coefficient c may be used to infer the water quality parameters (such as concentrations of chlorophyll a, suspended minerals, and dissolved organic carbon) contributing to the light scattering and light absorption processes occurring within a natural water body. This work, performed in the optically complex waters of Lake Ontario, resulted from coordinated efforts of optical and water quality data collection, multiple regression, radiative transfer theory and optimization technique analysis which interwove in the manner schematically illustrated in the flow diagram of Figure 1. The directly measured *in situ* optical parameters R, k and c are relatable, through the radiative transfer equation, to the inherent optical properties of a natural water mass (Gordon *et al*., 1975; Di Toro, 1978). These inherent optical properties are a direct consequence of the individual optical properties of each of the organic and inorganic, suspended and dissolved, scattering and absorption centres comprising the water mass under consideration. The multi-component nature of optically-complex inland water masses is globally appreciated, and the number of physical, chemical and biological components that interact with impinging above-water radiation can very quickly become unmanageably large for water quality models with the ambitious intent to delineate a myriad of classifications and subclassifications of inorganic materials and a myriad of species and subspecies of organic materials. Our inland water quality model restricted itself to five broad component categories and considered the scattering and absorption properties of chlorophyll *a* (corrected for phaeophytin contamination), suspended mineral (irrespective of type), dissolved organic carbon, non-living organics, and pure water. If it is assumed that the inherent optical properties display additive characteristics, then multiple regression or optimization analyses techniques applied to directly-measured optical properties and simultaneously acquired water quality data enable a determination of the scattering and absorption optical cross sections (i.e., the amount of scattering and absorption per unit concentration of each aquatic component considered within the multi-component water quality model) as a function of wavelength over the entire visible spectrum. The determination of these optical cross sections provides the essential linkages between the inherent optical properties of a water mass and its water quality parameters.

Once the optical cross sections are known, the radiative transfer equations may be readily utilized to determine an anticipated subsurface volume reflectance spectrum R(λ) over the entire visible spectrum. Using a set of cross-section spectra determined in western Lake Ontario (Bukata et al., 1985), Figures 2, 3 and 4 illustrate representative samples of the catalogue of anticipated subsurface irradiance reflectance (volume reflectance) spectra which may be generated point-by-point for a selected variety of water masses displaying variable concentrations of, say, chlorophyll a, suspended minerals and dissolved organic carbon. Figure 2 illustrates a family of subsurface irradiance reflectance spectra for a water mass in which suspended mineral (SM) and dissolved organic carbon (DOC) concentrations are kept fixed at zero, and chlorophyll a concentrations are allowed to vary. Figure 3 illustrates a family of subsurface irradiance reflectance spectra for a water mass in which DOC concentration is kept fixed at zero, chlorophyll a concentration is kept fixed at 0.05 mg m^{-3}, and SM concentration is allowed to vary. Figure 4 illustrates a family of subsurface irradiance reflectance spectra for a water mass in which chlorophyll a concentration is kept fixed at

1.00 mg m^{-3}, SM concentration is kept fixed at 0.05 g m^{-3}, and DOC concentration is allowed to vary. Figures 2, 3 and 4 clearly indicate the changes in both magnitude of volume reflectance and aquatic colour that accompany changes in concentrations of three principal water quality indicators.

Returning to a consideration of Figure 1, the flow diagram suggests that the determination of the multi-component visible wavelength spectra of the optical cross sections will lead to the development of a subsurface predictive water quality capability in which theoretically-generated volume reflectance spectra may be directly compared to *in situ* measurements of volume reflectance spectra. As mathematically shown in Bukata *et al*. (1985) multivariate optimization techniques such as the Levenberg-Marquardt finite difference algorithms (Levenberg, 1944; Marquardt, 1963) are required for the extraction of water quality information from such subsurface volume reflectance spectra. In order to apply such subsurface water quality modelling to space-acquired data, the subsurface volume reflectance spectra must first be transferred through the water-air interface (as illustrated in Bukata *et al*., 1988), and in conjunction with appropriate atmospheric models be transferred through the terrestrial atmosphere to satellite altitudes.

DIFFICULTIES ASSOCIATED WITH CHLOROPHYLL ESTIMATIONS BOTH FROM BELOW AND FROM ABOVE THE AIR/WATER INTERFACE

The physical principles, upon which is based the multi-component optical modelling activity schematically illustrated in Figure 1, are sound within the current level of aquatic understanding. The absorption and scattering properties of the suspended and dissolved materials comprising natural water masses, along with the properties of the impinging above-surface irradiance, will dictate the subsurface irradiance reflectance (volume reflectance) spectra that will be experimentally measured within those water masses. This subsurface volume reflectance, in turn, can be converted into an estimation of the water quality parameters (suspended mineral, chlorophyll, dissolved organic carbon, etc.) only if the optical cross sections (i.e., the amount of absorption and scattering per unit concentration) of those water quality parameters are known. Further, the intervening atmosphere between the aquatic resource and the remote optical sensor directly modulates the estimate of subsurface volume reflectance inferred at the space observation platform.

While there is an increasing effort, on a global scale, to obtain precise information on the optical cross sections of aquatic components, the results of such efforts have been far from universally applicable. Certainly there has been general agreement concerning rather broad (in some cases) ranges of values of such cross sections, as well as the realization that such optical cross sections are not only geographically and species dependent, but also temporally dependent. Consequently, a major obstacle to the remote estimation of aquatic chlorophyll concentrations from space has been an inherent inability to reproduce experimentally equivalent and/or reliably extrapolatable values for such critical parameters. Our own work in Lake Ontario directly reflects this situation. Two independent coordinated optical/water quality data sets were obtained in western Lake Ontario during the 1979 field season. Although similar wavelength spectra for the scattering and absorption cross sections of suspended mineral and dissolved organic carbon and for the scattering cross section of chlorophyll appear to be reasonably appropriate for both data sets, each of the data sets were determined to require significantly dissimilar absorption cross-section spectra for chlorophyll. These two absorption cross-section spectra are illustrated in Figure 5. The two obvious features of Figure 5 appear to be a) reasonable agreement concerning the absorption peak at the red end of the visible spectrum, and b) the largest departures from constancy occurring at the blue end of the spectrum, although departures from constancy certainly include the green wavelengths. One of the two chlorophyll absorption curves observed in Lake Ontario displays a distinct absorption peak near 450 nm, while the other Lake Ontario absorption curve does not.

Morel and Bricaud (1981) have discussed the problems that originate from the inconstancy of the absorption cross section for chlorophyll a and have illustrated that large departures from constancy exist not only for several distinct species of chlorophyll-bearing cells but also for variations (cell size, cell structure, cell stability, etc.) within the cells of the same species.

A typical, but by no means exhaustive, representation of the vast discrepancies that exist among various determinations of the absorption cross sections of chlorophyll a (a_{chl}) is shown in Figure 6 wherein are plotted not only the two observed data sets of Figure 5, but also representative results of other workers. The various curves of Figure 6 display, in addition to numerical differences, variations in rising and falling slopes. As discussed in considerable detail in Bukata et al. (1985), such variable slopes dramatically impact the shape of the directly measured subsurface irradiance reflectance spectra. The Lake Ontario curve C appears to be a lower-limit envelope to the plotted data. This, however, does not indicate that Lake Ontario contains chlorophyll-bearing biota characterized by minimal absorption cross sections, since many other works (data not shown) have obtained smaller values of a_{chl} than comprise curve C, just as values of a_{chl} larger than those comprising curve A' have likewise been observed.

THE OCEAN IN THE GAIA HYPOTHESIS

It is a widely-held belief that the earth's climate and physico-chemical composition is unique (at least within our solar system) in its favourable disposition towards its support of life. It is an even more widely-held belief that relatively small changes in the dynamically balanced state that exists among such climatic and physicochemical components could render such life-support capabilities completely unsuitable for contemporary biota. Less widely-held, but rapidly growing in support, is the theory first propounded by Lovelock (1972) and Lovelock and Margulis (1974), that the biosphere serves as more than merely a passive accommodation for the environment. According to the above workers, the biosphere (or more specifically, individual life forms) acts in a proactive manner so as to control the global environment and thereby optimize the environment's capacity for sustaining life. Such a biosphere "life force" and the theory which purports its existence bears the name Gaia, after the Greek personification of Mother Earth. The Gaia Theory, of course, may forever remain directly unverifiable since the existence of Gaia is admittedly hypothetical. Being a creature of hypothesis, Gaia's ascribed properties and powers are in direct conflict with those of the physical and chemical parameters which have traditionally become considered as climate regulators. Without intentionally fueling such controversies, suffice to say that the strongest (albeit circumstantial) evidence for the support of the Gaia hypothesis is that throughout the continuum of time generally ascribed to the presence of life on earth (over $3x10^9$ years), the chemical and physical properties of the earth's environment have never been at variance with those optimal conditions required for the support of life. Some life-forms have ceased to exist and new life-forms have apparently been discovered, but the environmental conditions required to sustain life on earth have themselves been sustained.

Since life abounds within the global water masses, aquatic resources form an integral component of the Gaia speculations. Workers such as Twomey (1977), Shaw (1987) and Meszaros (1988) have extended the Gaia hypothesis to atmospheric aerosols and suggest that the aerosol produced by the atmospheric oxidation of sulphur gases from biota may directly impact climate. More specifically, Charlson _et al_. (1987) speculate that the dimethylsulphide emitted by oceanic phytoplankton directly serves as cloud-condensation nuclei which modulate cloud reflectance and therefore the earth's radiation budget. Charlson _et al_. (1987) thus suggest that the oceanic phytoplankton act as biological regulators of the earth's climate, a suggestion in agreement with the speculations of Shaw (1987) and Meszaros (1988). Such global climate control by oceanic phytoplankton, however, is challenged by Schwartz (1988) who indicates that anthropogenic sulphur dioxide, which exceeds marine emissions of dimethylsulphide, shows no counterpart influence in either the present cloud component of planetary albedo or the temperature records of the past century.

Irrespective, however, of the controversial role of Gaia in ocean/atmosphere dynamics, it is reasonable to consider a feedback loop as existing between marine phytoplankton and downwelling irradiance (both solar and sky) above the air-water interface but below the clouds. It is also reasonable to consider directlymeasureable chlorophyll concentrations as a surrogate for phytoplankton populations, and therefore suggest a feedback loop between remote measurements of chlorophyll concentrations and downwelling irradiance. Whether the phytoplankton passively respond to or proactively dictate (or both) specific variations in the downwelling atmospheric irradiance it is further reasonable to assume that phytoplanktonic adaptation (whether passive or proactive) will manifest, among other things, as physical changes (size, shape, etc.) in the chlorophyll-bearing biota. These physical changes will generate corresponding changes in the optical properties, and therefore the optical cross sections of chlorophyll.

The optical cross sections of chlorophyll therefore, are subject to variability directly associated with spatial locations, seasonal cycles, and species definition. They also may be a function of the very climate changes that they are being used to monitor. This latter function is currently an unknown factor, the complexity of which may be a direct consequence of the controversial role of Gaia. Even without the added complexity of Gaia and the suggested feedback loop between chlorophyll concentrations and downwelling irradiance, the need to determine accurate values of optical cross sections is illustrated by the recent work of Andre and Morel (1989) who simulate the impact of varying atmospheric ozone content on the remote estimates of marine phytoplankton utilizing biooptical algorithms described for the NIMBUS Coastal Zone Colour Scanner. The authors report that the use of mean climatology values for ozone content and barometric pressure (rather than the actual values of ozone and pressure at time of measurements) can lead to misestimates of phytoplanktonic pigment concentrations of as much as a factor of two. It is reasonable to consider that such misestimates for the more optically complex inland and coastal aquatic regimes would be even larger. Since chlorophyll concentrations respond to changes in such climatic factors as ozone and pressure, the need to reliably assess chlorophyll concentrations becomes all the more imperative. Because of the substantial departures in optical complexities between inland and oceanic waters (Morel, 1988; Jerome et al., 1988) it is quite possible that the CZCS algorithms developed for oceanic waters are not directly applicable to inland, coastal, or estuarine waters. Further, the lake and river low-level remote sensing methodologies reported by such workers as Bukata et al. (1988), Mittenzwey et al. (1988), Jerome et al. (1989) and Gittelson and Nikanorov (1988) are both time and space limited. One obvious solution to such dilemmas is the obtaining of reliable optical cross sections at principal global locations.

CONCLUDING REMARKS

The earth is currently subject to both natural and anthropogenic climatic change influences which have necessitated global participation in ecosystematic solar/terrestrial research programs of unprecedented complexities. That the terrestrial water masses comprise a principal target for such ecosystematic research activities is undeniable. The exact role of aquatic resources in the responsive and/or proactive feedback loops within the terrestrial and inner solar cavity environments, while generally understood and appreciated, is still not uniquely defined in terms of causal relationships. With the advent of global climatology programs such as IGBP, GCIH and WOCE and their key dependence on reliable optical measurements from space platforms, the need to determine biomass/chlorophyll concentrations from such remote platforms is accentuated.

The spectrooptical return from a natural water body is a convoluted consequence of the scattering and absorption centres residing within that natural water body. The complexity of such convolutions is a direct consequence of the number and nature of the competitive scattering and absorption centres indigenous to the aquatic locale. Inland water-mass types (lakes, rivers, estuaries, groundwater, oceanic coastal regions, etc.) possess, in general, a considerably higher order optical complexity than do their oceanic counterparts. Chlorophyll retrieval algorithms for ocean waters developed for such space vehicles as NIMBUS are, therefore, not necessairly appropriate for application to chlorophyll retrieval from inland waters. Such algorithms may, in fact, lack sufficient reliability for oceanic monitoring. The direct linkages between direct measurements of above water radiance and subsurface water quality parameters (whether inland or oceanic) are provided by the optical cross sections (amount of scattering and absorption per unit concentration of each relevant water quality component). These optical cross sections (particularly those of chlorophyll *a*) are functions of species, time and space, and possibly also a function of Gaia.

Despite such cross-sectional variability, we have argued that global measurements of chlorophyll, and, therefore, global measurements of optical cross sections are essential for the successful interweaving of the role of aquatic resources into the overall assessment of the multidisciplinary program of climate change research. Such optical cross sections must be determined for each major (in volume and/or environmental influence) inland water-mass type, and possibly even for oceanic waters.

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FIGURE CAPTIONS

Figure 1. Flow diagram outlining the activities in the development of remote sensing optical water quality models based on the specific absorption and scattering cross sections of the component water quality parameters.

Figure 2. Subsurface irradiance reflectance spectra for various chlorophyll a concentrations in a water mass for which the SM and DOC concentrations are kept fixed at zero.

Figure 3. Subsurface irradiance reflectance spectra for various SM concentrations in a water mass containing a small fixed amount of chlorophyll a and zero DOC.

Figure 4. Subsurface irradiance reflectance spectra for various DOC concentrations in a water mass for which the SM concentration is kept fixed at 0.05 g m^{-3} and the chlorophyll a concentration is kept fixed at 1.00 mg m^{-3}.

Figure 5. A comparison of the chlorophyll a absorption cross section spectra obtained from the independent optical/water quality data sets in western Lake Ontario.

Figure 6. An intercomparison of a number of independent attempts to determine the absorption cross sections of chlorophyll a.

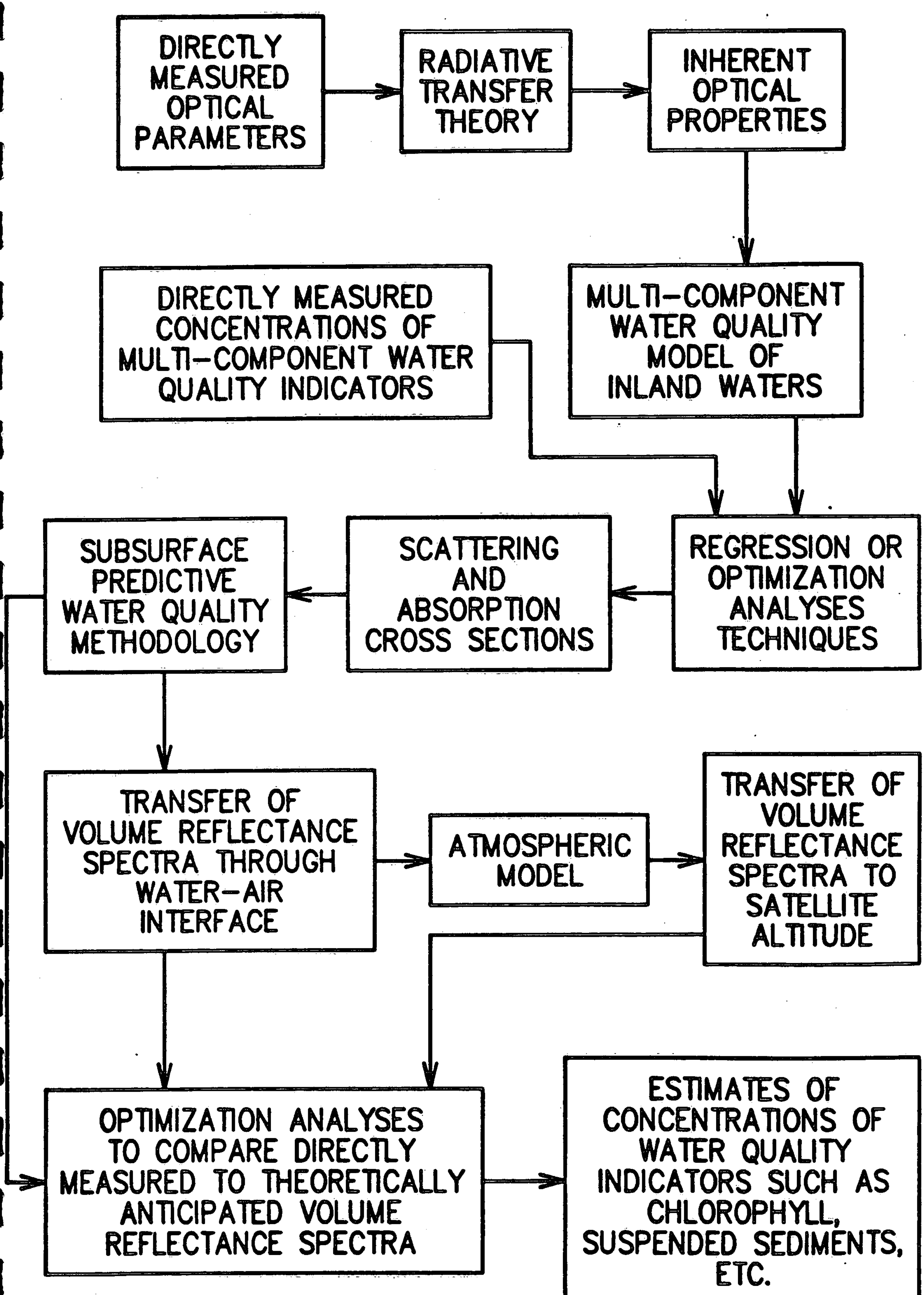
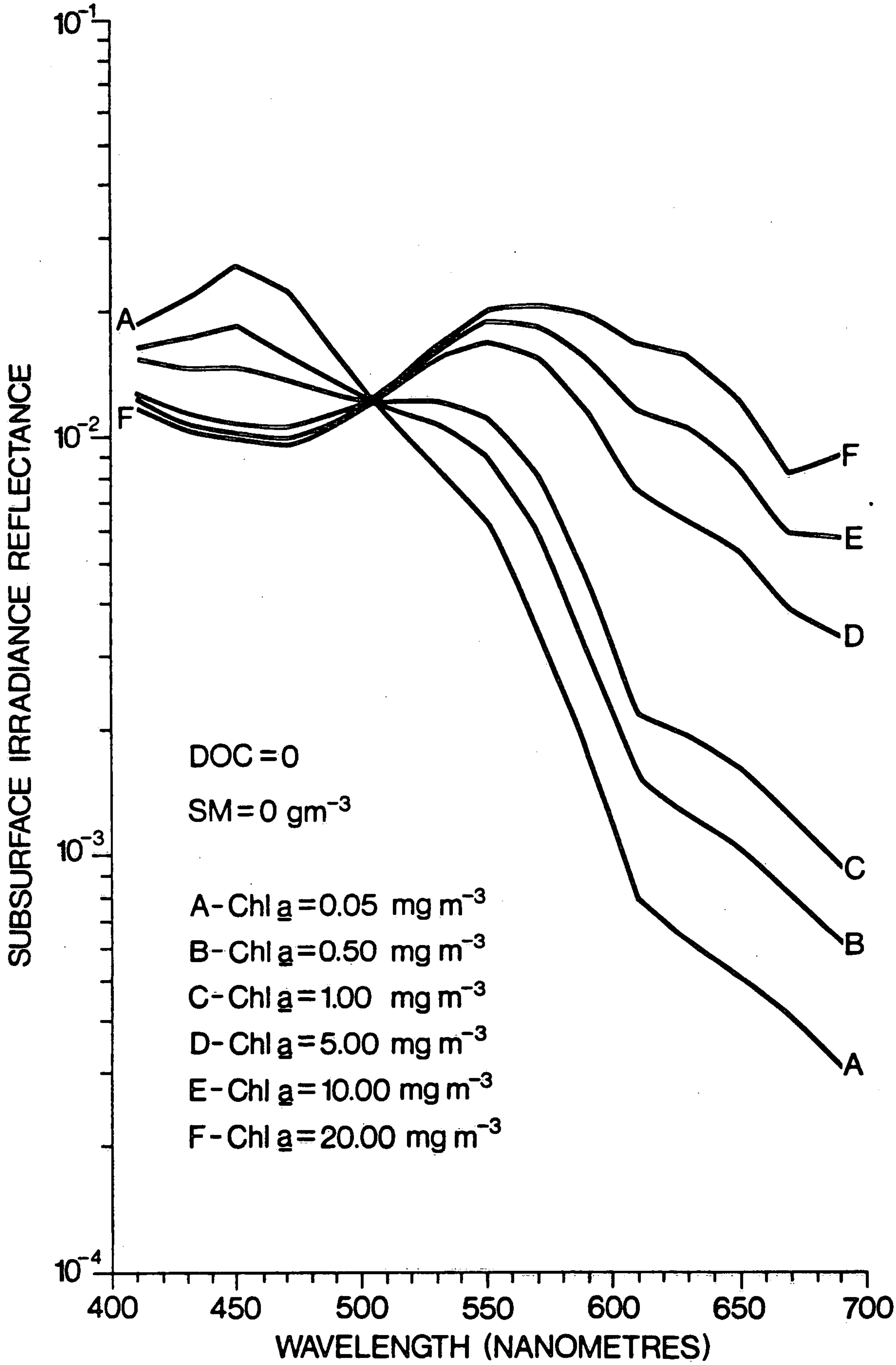
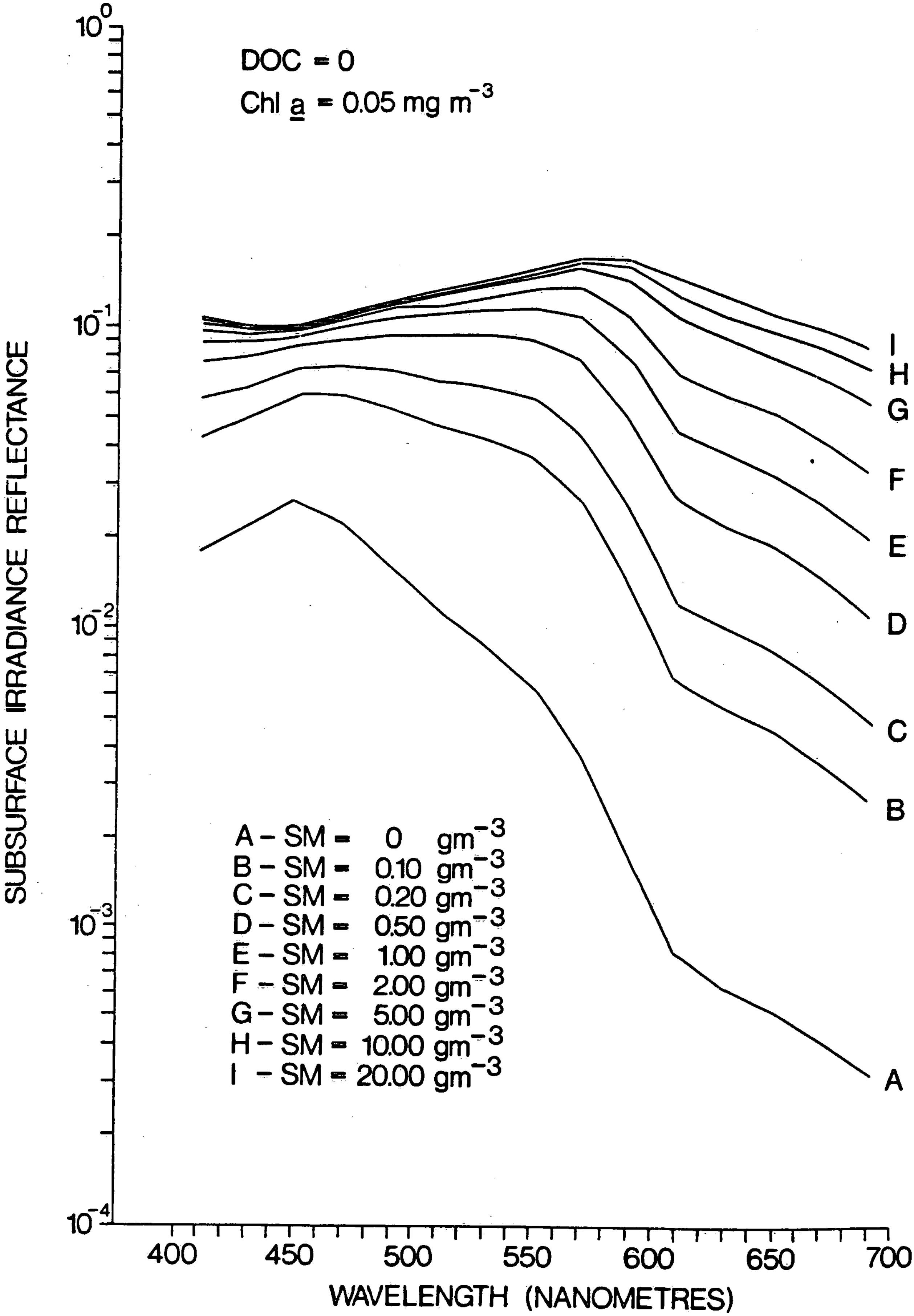

DIRECTLY MEASURED OPTICAL PARAMETERS
RADIATIVE TRANSFER THEORY
INHERENT OPTICAL PROPERTIES
DIRECTLY MEASURED CONCENTRATIONS OF MULTI-COMPONENT WATER QUALITY INDICATORS
MULTI-COMPONENT WATER QUALITY MODEL OF INLAND WATERS
SUBSURFACE PREDICTIVE WATER QUALITY METHODOLOGY
SCATTERING AND ABSORPTION CROSS SECTIONS
REGRESSION OR OPTIMIZATION ANALYSES TECHNIQUES
TRANSFER OF VOLUME REFLECTANCE SPECTRA THROUGH WATER-AIR INTERFACE
ATMOSPHERIC MODEL
TRANSFER OF VOLUME REFLECTANCE SPECTRA TO SATELLITE ALTITUDE
OPTIMIZATION ANALYSES TO COMPARE DIRECTLY MEASURED TO THEORETICALLY ANTICIPATED VOLUME REFLECTANCE SPECTRA
ESTIMATES OF CONCENTRATIONS OF WATER QUALITY INDICATORS SUCH AS CHLOROPHYLL, SUSPENDED SEDIMENTS, ETC.

FIG. 1



10^{-1}
10^{-2}
10^{-3}
10^{-4}
SUBSURFACE IRRADIANCE REFLECTANCE
400
450
500
550
600
650
700
WAVELENGTH (NANOMETRES)
A
F
B
C
D
E
DOC = 0
SM = 0 gm^{-3}
A - Chl a = 0.05 mg m^{-3}
B - Chl a = 0.50 mg m^{-3}
C - Chl a = 1.00 mg m^{-3}
D - Chl a = 5.00 mg m^{-3}
E - Chl a = 10.00 mg m^{-3}
F - Chl a = 20.00 mg m^{-3}

FIG 2



DOC = 0
Chl a = 0.05 mg m-3
SUBSURFACE IRRADIANCE REFLECTANCE
10^0
10^-1
10^-2
10^-3
10^-4
400
450
500
550
600
650
700
WAVELENGTH (NANOMETRES)
I
H
G
F
E
D
C
B
A
A – SM = 0 gm-3
B – SM = 0.10 gm-3
C – SM = 0.20 gm-3
D – SM = 0.50 gm-3
E – SM = 1.00 gm-3
F – SM = 2.00 gm-3
G – SM = 5.00 gm-3
H – SM = 10.00 gm-3
I – SM = 20.00 gm-3

FIG. 3

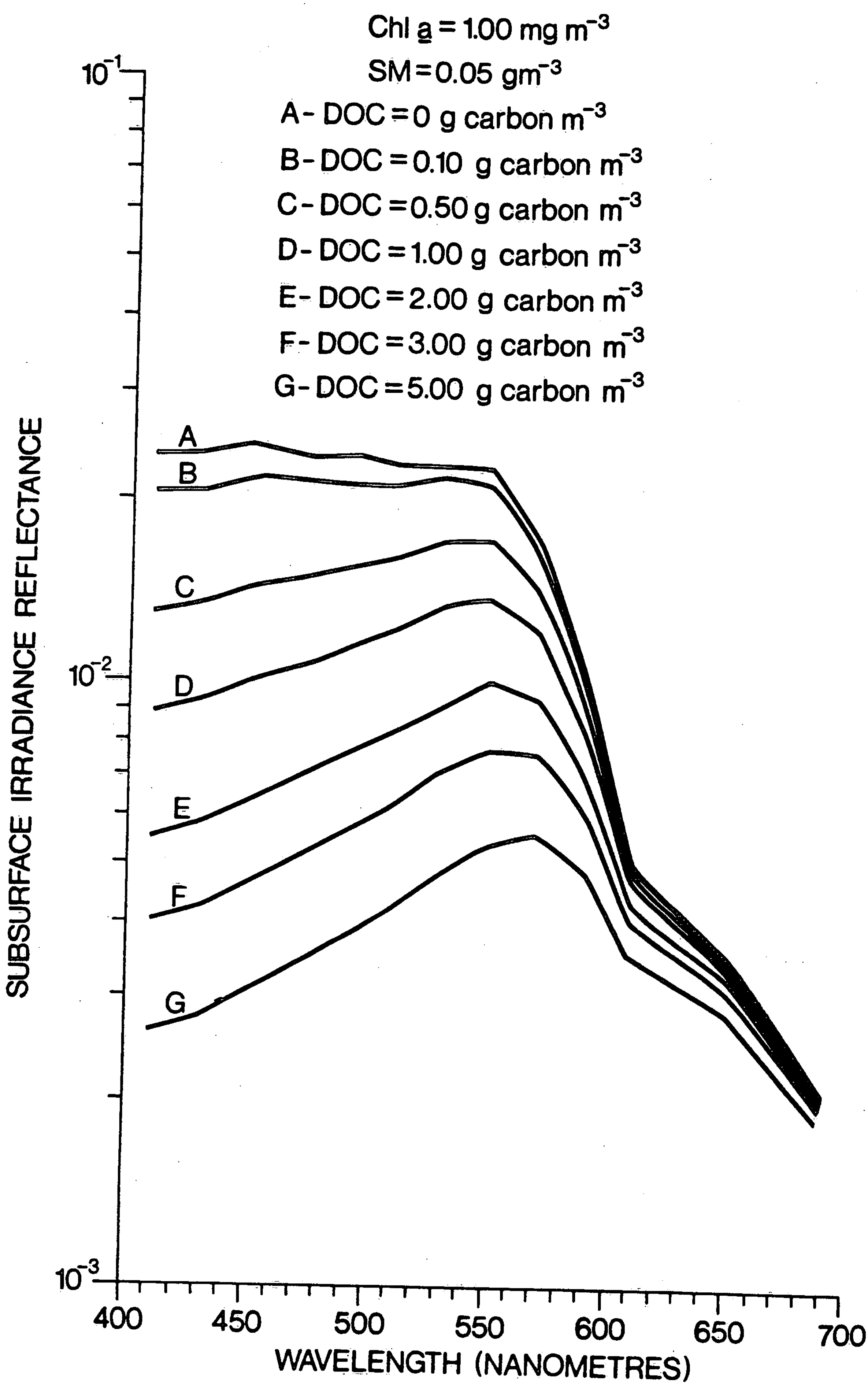

Chl a = 1.00 mg m-3
SM = 0.05 gm-3
A - DOC = 0 g carbon m-3
B - DOC = 0.10 g carbon m-3
C - DOC = 0.50 g carbon m-3
D - DOC = 1.00 g carbon m-3
E - DOC = 2.00 g carbon m-3
F - DOC = 3.00 g carbon m-3
G - DOC = 5.00 g carbon m-3
A
B
C
D
E
F
G
10-1
10-2
10-3
SUBSURFACE IRRADIANCE REFLECTANCE
400
450
500
550
600
650
700
WAVELENGTH (NANOMETRES)

FIG. 4

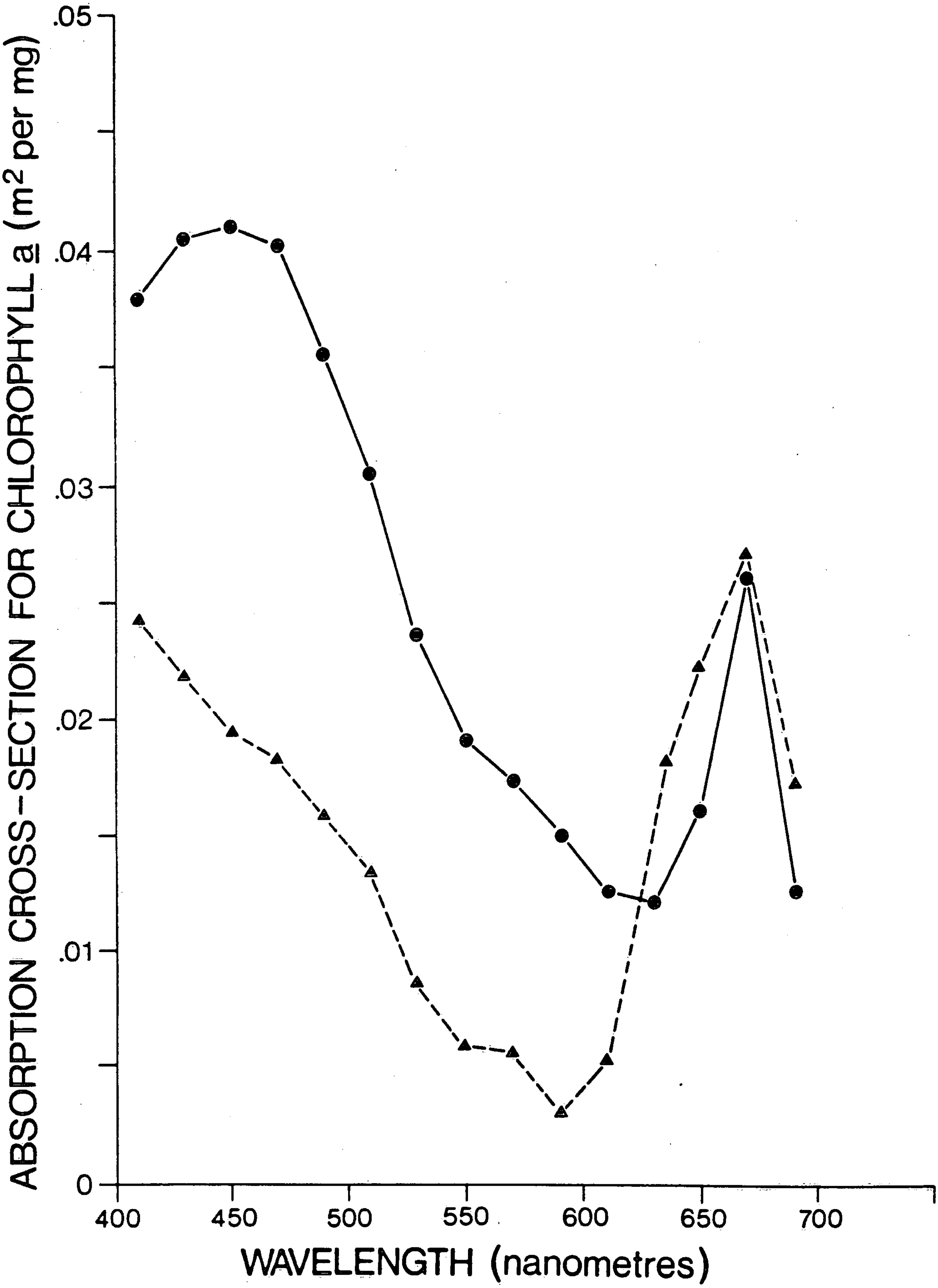
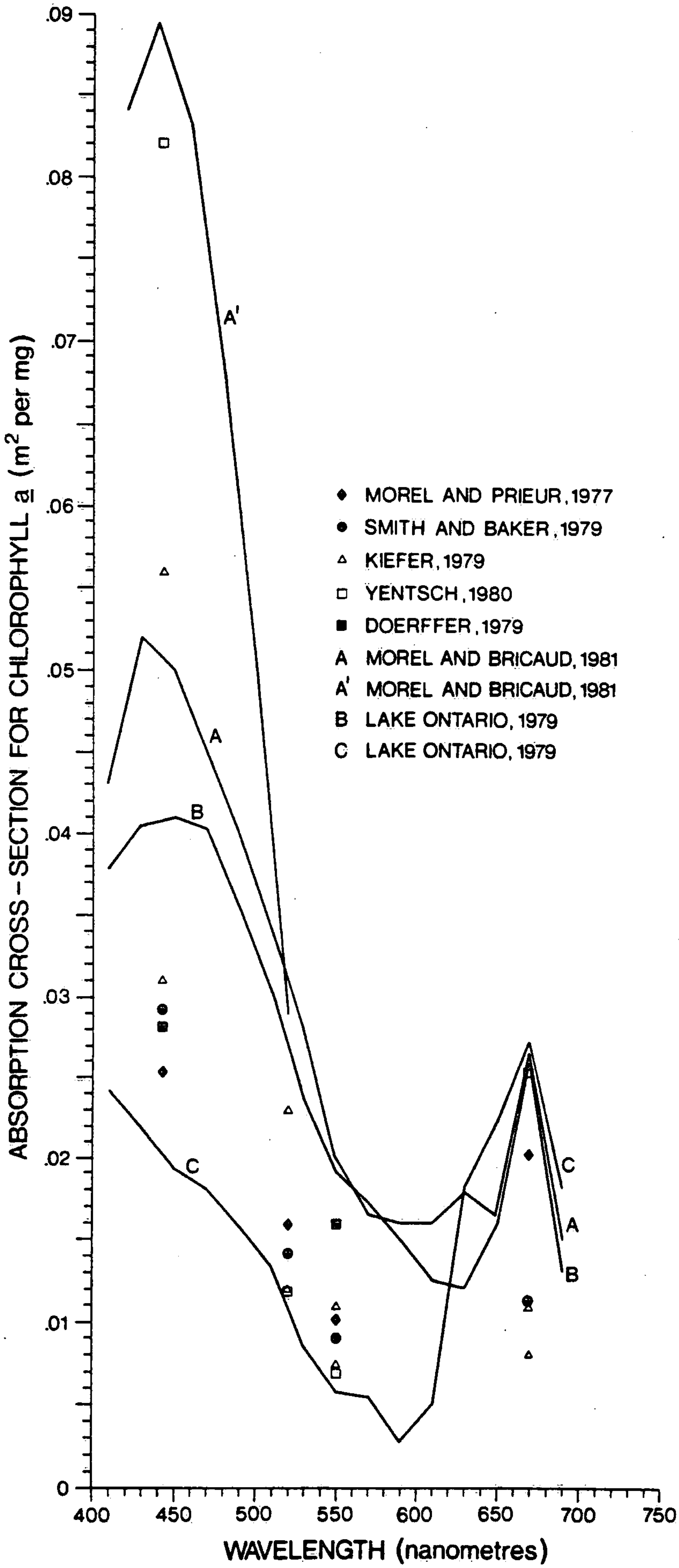

.05
.04
.03
.02
.01
0
ABSORPTION CROSS-SECTION FOR CHLOROPHYLL a (m2 per mg)
400
450
500
550
600
650
700
WAVELENGTH (nanometres)

FIG. 5



ABSORPTION CROSS-SECTION FOR CHLOROPHYLL a (m^2 per mg)
WAVELENGTH (nanometres)
.09
.08
.07
.06
.05
.04
.03
.02
.01
0
400
450
500
550
600
650
700
750
MOREL AND PRIEUR, 1977
SMITH AND BAKER, 1979
KIEFER, 1979
YENTSCH, 1980
DOERFFER, 1979
A MOREL AND BRICAUD, 1981
A' MOREL AND BRICAUD, 1981
B LAKE ONTARIO, 1979
C LAKE ONTARIO, 1979
A'
A
B
C

FIG. 6