การพัฒนาอัลกอริทึมสีของน้ำทะเลสำหรับบริเวณอ่าวไทยตอนบน

นายธชณัฐ ภัทรสถาพรกุล

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิทยาศาสตรมหาบัณฑิต

สาขาวิชาวิทยาศาสตร์ทางทะเล ภาควิชาวิทยาศาสตร์ทางทะเล

คณะวิทยาศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย

ปีการศึกษา 2547

ISBN 974-53-1497-8

DEVELOPMENT OF OCEAN COLOUR ALGORITHMS FOR THE UPPER GULF OF THAILAND

Mr. Tachanat Bhatrasataponkul

A Thesis Submitted in Partial Fulfillment of the Requirements

for the Degree of Master of Science in Marine Science

Department of Marine Science

Faculty of Science

Chulalongkorn University

Academic Year 2004

ISBN 974-53-1497-8

Thesis Title	Development of Ocean Colour Algorithms for the Upper Gulf of Thailand
By	Mr. Tachanat Bhatrasataponkul
Field of Study	Marine Science: Physical Oceanography
Thesis Advisor	Associate Professor Absornsuda Siripong
Thesis Co-advisor	Darasri Dowreang, Ph.D.

Accepted by the Faculty of Science, Chulalongkorn University in Partial Fulfillment of the Requirements for the Master's Degree

………………………………………….……Dean of the Faculty of Science

(Professor Piamsak Menasveta, Ph.D.)

THESIS COMMITTEE

………………………………………….……Chairman

(Assistant Professor Charoen Nitithamyong, Ph.D.)

………………………………………….……Thesis Advisor

(Associate Professor Absornsuda Siripong)

………………………………………….……Thesis Co-advisor

(Darasri Dowreang, Ph.D.)

…………………………………………….....Member

(Supichai Tangjaitrong, Ph.D.)

………………………………………….……Member

(Assistant Professor Thaithaworn Lirdwitayaprasit, Ph.D.)

ธชณัฐ ภัทรสถาพรกุล : การพัฒนาอัลกอริทึมสีของน้ำทะเลสำหรับบริเวณอ่าวไทยตอนบน. (DEVELOPMENT OF OCEAN COLOUR ALGORITHMS FOR THE UPPER GULF OF THAILAND) อ.ที่ปรึกษา : รองศาสตราจารย์ อัปสรสุดา ศิริพงศ์, อ.ที่ปรึกษาร่วม : ดร. ดาราศรี ดาวเรือง, 96 หน้า. ISBN 974-53-1497-8.

ในการพัฒนาอัลกอริทึมสีของน้ำทะเลสำหรับบริเวณอ่าวไทยตอนบน เพื่อตรวจวัดปริมาณของคลอโรฟิลด์เอ (CHLA) ตะกอนแขวนลอยรวม (TSS) สารอินทรีย์ละลายน้ำ (CDOM) และค่าสัมประสิทธิ์ Kd490 โดยทำการออกสำรวจภาคสนามทั้งหมด 83 สถานี ในระหว่างการออกเรือ 5 ครั้ง ระหว่างเดือนตุลาคมและธันวาคม พ.ศ. 2546 และเดือนมกราคม พฤษภาคม และตุลาคม พ.ศ. 2547 ซึ่งครอบคลุมต้นและปลายฤดูลมมรสุมตะวันตกเฉียงใต้และตะวันออกเฉียงเหนือ โดยใช้เครื่องมือ Profiling Reflectance Radiometer (PRR-600) วัดค่าตัวแปรเชิงแสงในน้ำทะเล ณ ความยาวคลื่นอ้างอิง เพื่อคำนวณค่า Remote Sensing Reflectance ซึ่งใช้ในการพัฒนาอัลกอริทึมดังกล่าว ผลการศึกษาพบว่าอัลกอริทึมที่พัฒนาขึ้นสามารถนำไปใช้ตรวจวัดพารามิเตอร์ดังต่อไปนี้ ด้วยผลความถูกต้องที่ยอมรับได้

$$\text{CHLA (mg/m}^3) = 1.1828(\text{Rrs520/Rrs565})^{-4.8367}$$

$$\text{TSS (g/m}^3) = 99.355(\text{Rrs670})^{0.5746}$$

$$\text{CDOM 412 (m}^{-1}) = 0.362(\text{Rrs412/Rrs565})^2 - 0.929(\text{Rrs412/Rrs565}) + 0.586$$

$$\text{Kd 490 (m}^{-1}) = 0.2411(\text{Rrs490/Rrs565})^{-1.2753}$$

การศึกษานี้ได้อธิบายรูปแบบการแพร่กระจายตัวของปริมาณคลอโรฟิลด์เอ ตะกอนแขวนลอยรวม และสารอินทรีย์ละลายน้ำ ผลการศึกษาพบว่าความสามารถในการแปรผันเชิงแสงของน้ำทะเลในบริเวณอ่าวไทยตอนบนขึ้นอยู่กับอิทธิพลหลักดังนี้ คือ ปริมาณและองค์ประกอบของน้ำท่าจากแม่น้ำสี่สายหลัก การแขวนลอยกลับคืนสู่มวลน้ำของตะกอนพื้นท้องน้ำ รวมไปถึงองค์ประกอบของตะกอนแขวนลอย

ภาควิชา..........วิทยาศาสตร์ทางทะเล............	ลายมือชื่อนิสิต..
สาขาวิชา.........วิทยาศาสตร์ทางทะเล...........	ลายมือชื่ออาจารย์ที่ปรึกษา..
ปีการศึกษา.................2547..........................	ลายมือชื่ออาจารย์ที่ปรึกษาร่วม.....................................

457 22522 23 :MAJOR MARINE SCIENCE

KEY WORD : OCEAN COLOUR ALGORITHM / OPTICAL PROPERTIES / UPPER GULF OF THAILAND

TACHANAT BHATRASATAPONKUL: DEVELOPMENT OF OCEAN COLOUR ALGORITHMS FOR THE UPPER GULF OF THAILAND. THESIS ADVISOR : ASSOC. PROF. ABSORNSUDA SIRIPONG, THESIS CO-ADVISOR : DARASRI DOWREANG, Ph.D., 96 pp. ISBN 974-53-1497-8.

A study was investigated in the Upper Gulf of Thailand with the aim of developing in-water algorithms for the retrievals of chlorophyll-a (CHLA), total suspended sediment (TSS), coloured dissolved organic matter (CDOM) and diffuse attenuation coefficient for downwelling irradiance at 490 nm (Kd490). Shipboard field observations were made at totally 83 stations during 5 cruises covering early and late southwest and northeast monsoons in the year 2003-2004. The optical data were recorded using the Profiling Reflectance Radiometer (PRR-600) in order to calculate the remote sensing reflectance (Rrs) at some reference wavelengths. Results showed that the improved algorithms based on the empirical approach enabled the estimations of the following parameters with acceptable precision.

$$\text{CHLA } (mg/m^3) = 1.1828(Rrs520/Rrs565)^{-4.8367}$$

$$\text{TSS } (g/m^3) = 99.355(Rrs670)^{0.5746}$$

$$\text{CDOM } 412\ (m^{-1}) = 0.362(Rrs412/Rrs565)^2 - 0.929(Rrs412/Rrs565) + 0.586$$

$$\text{Kd } 490\ (m^{-1}) = 0.2411(Rrs490/Rrs565)^{-1.2753}$$

The patterns of remote sensing reflectance were related to the distributions of the optically active constituents. Results showed that the optical variability of the Upper Gulf of Thailand is mainly influenced by freshwater inflows and resuspension of bottom sediment as well as sediment composition and characteristics.

Department……....Marine Science……….	Student's signature…………………………….……..
Field of study……..Marine Science……….	Advisor's signature………………………………..
Academic year….……...2004…….….….…	Co-advisor's signature……………………………

ACKNOWLEDGEMENTS

The support provided by the following organizations are appreciated, namely, the Geo-Informatics and Space Technology Development Agency (public organization) for research fund; Graduate School, Chulalongkorn University for financial support; Marine Science Department, Faculty of Science, Chulalongkorn University for all facilities; Faculty of Fisheries, Nagasaki University for laboratory and data analysis techniques; Sriracha Fisheries Research Center, Kasetsart University for research vessel KASETSART I.

First and foremost, I would like to express my sincere gratitude to all those who served as thesis committees and curricular committees for their encouragements throughout my study and their invaluable comments and suggestions towards this thesis.

It is an impossible task to list all those to whom I am indebted in one way or another for giving specific help or stimulating the ideas which has gone into this thesis. However, I will try to do so, and apologize in advance for those I inadvertently forget: Patama Singhruck, Akihiko Tanaka, Hiroaki Sasaki, Hiroshi Kobayashi, Mitsuhiro Toratani, Supichai Tangjaitrong, Charoen Nitithamyong, Absornsuda Siripong, Darasri Dowreang, Thaithaworn Lirdwitayaprasit, Nittharatana Paphavasit, Ajcharaporn Piumsomboon, Sirichai Dharmvanij, Pramot Sojisuporn, Wilaiwan Utoomprurkporn, Anond Snidvongs, Chatchawan Bawornkittiwong, Suratta Bunsomboonsakul, Chalermrat Sangmanee, Jitraporn Phaksopa and Patamaporn Mhadnui.

I also wish to thank all staff and colleagues in the Marine Science Department who have made it a pleasure to study. They made my time there both enjoyable and intellectually stimulating. Throughout seven years at Chulalongkorn University, I have broadened my perspectives and learned many ways of thinking and approaching issues with totally 240 course credits in various fields of study both areas of sciences and arts.

Last but not least, my deepest regard goes to Professor Satsuki Matsumura. I am grateful to Professor Ishizaka Joji and Professor Hiroshi Kawamura for their supports.

Most of all, I could never reach this point without loving support of my family.

CONTENTS

Page

LIST OF TABLES

Table Page

LIST OF FIGURES

Figure Page

Figure Page

CHAPTER I

INTRODUCTION

1.1 Importance of the study

Ocean colour information has become an important remotely sensed parameter and used for the assessment of water quality characteristics, primary production rate, and trophic status of natural water bodies. An ocean colour algorithm is a formula or mathematical procedure for deriving water properties from the radiance measured by the satellite ocean colour sensor. The algorithm is based on an underlying forward model of reflectance that gives water-leaving radiance as a function of water properties, including the concentrations of optically active constituents. In Principle, there are at least three in-water constituents that affect optical properties of coastal waters. These are phytoplankton pigments which are indexed by the chlorophyll-*a* concentration, total suspended sediments, and coloured dissolved organic matter which is indexed by its absorption at a reference wavelength.

The optical properties of the Upper Gulf of Thailand are much complex due to variable proportion of materials from terrestrial discharges especially the four main rivers namely the Mae Klong, the Tha Chin, the Chao Phraya, and the Bang Pakong flowing into from the western to the eastern part, respectively. As a result, reliable algorithms are currently limited to season and site specific examples. Obviously, the algorithms must be parameterized for regional waters in order to retrieve the accurate data in the specific areas. Therefore, marine optical variability and its in-water algorithms do need to be improved for the Upper Gulf of Thailand.

Although many studies on oceanographic survey in the Upper Gulf of Thailand have long been carried out to date, those in relation to optical observation have never ever existed. With respect to the better understanding on marine optical environment which affects living organisms together with water quality, the present study attempts to provide additional information on optical oceanography in the Upper Gulf of Thailand.

1.2 Objectives

1. To develop the in-water algorithms for the Upper Gulf of Thailand.
2. To describe the optical variability of the Upper Gulf of Thailand.

1.3 Scope of the study

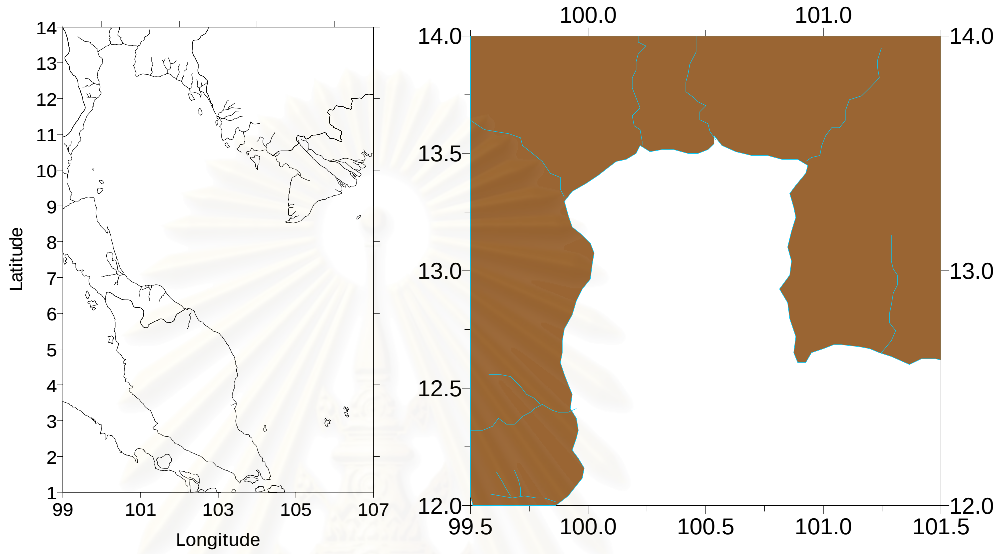

Figure 1.1 The Upper Gulf of Thailand

1. The study area covers the Upper Gulf of Thailand located between Latitude 12.5 – 13.5 ^{o}N and Longitude 100 – 101 ^{o}E.
2. Shipboard field observation was made at totally 83 stations throughout the Upper Gulf of Thailand during 5 cruises covering all seasonal cycle in the year 2003 – 2004.
3. Four in-water algorithms were developed for retrieval of chlorophyll-a, total suspended sediment, coloured dissolved organic matter and Kd490 in the Upper Gulf of Thailand.

1.4 Prospective outcomes

With respect to the better understanding on marine optical environment, algorithms can be used for:

1. assessment of primary production and trophic status of natural water body.
2. detecting and monitoring of red tide and suspended sediment distribution.
3. management of coastal environments and living resources.

CHAPTER II

LITERATURE REVIEW

2.1 Overview of the Upper Gulf of Thailand

The Upper Gulf of Thailand is the inner part of the Gulf of Thailand located between Latitude 12.5 - 13.5 ^{o}N and Longitude 100 – 101 ^{o}E. It is rather shallow with the mean depth of 15 meter. There are four main rivers namely the Mae Klong, the Tha Chin, the Chao Phraya, and the Bang Pakong flowing into the Upper Gulf from the western to the eastern part, respectively. These rivers not only influence on lower salinity by freshwater from terrestrial discharges, but also are important sources of organic and inorganic, suspended and dissolved materials, resulting from land weathering and the contaminants from catchment basin and watershed areas.

The circulation pattern in the Upper Gulf of Thailand is rotary-type circulation driven by the combination of tide and wind (Singhruck, 2002) as well as slight effect of density gradient as a result of river runoff particularly in the vicinity of river mouths (Oonpan, 2003). In addition to tidal pattern, the Upper Gulf of Thailand is dominated by mixed diurnal-dominate tide over the most areas, whilst mixed semidiurnal-dominate tide is prevalent in the adjacent areas of river mouths (Phaksopa, 2003). Physical transport processes play a very important role in controlling the extent of eutrophication. The standing wave and front in the Upper Gulf limit the exchange of coastal water with offshore water and thus contaminants accumulate in nearshore sediments (UNEP, 1995).

The area is influenced from the tropical monsoon wind system: the northeast and southwest monsoon. The dry northeast monsoon brings cool dry air from Siberia during November and March while the wet southwest monsoon brings warm moist air from Indian Ocean during May and October. These two monsoon conditions can directly affect riverine inputs concerning dissolved organic matter, suspended sediment and nutrients loading. Therefore, the study on spatial and temporal variations in the optical oceanographic survey cannot be overlooked for the Upper Gulf of Thailand.

2.2 Ocean colour remote sensing

The processes of absorption, scattering and, in some case, fluorescence influence the colour of the sea. Ocean colour examines in principle how quantitative information about the seawater and its content can be recovered from measurement of the light leaving the sea. From pioneering observational and theoretical foundations in the mid-twentieth century (Jerlov, 1968, 1976), the discipline of optical oceanography has now matured into the science of ocean optics (Spinrad *et al.*, 1994; Robinson, 2004). It is now applied in a wide range of oceanographic studies as diverse as photochemistry, mixed layer dynamics, biogeochemical cycles, primary production, marine pollution and fisheries oceanography (IOCCG, 1998, 1999, 2000, 2004).

The propagation of light in the ocean-atmosphere system is governed by the integral differential equation of radiative transfer (Gordon, 1994), which contains absorption and scattering parameters that are characteristics of the particular water body study. To consider underwater optical process, scattering and absorption deal with the variety of optically active constituents found in the sea. If a photon interacts with something that causes it to scatter before it is absorbed, there is a chance that it will be scattered back out of the sea and be seen by remote sensing. The other possible source of light underwater is from fluorescence, in which pigments such as chlorophyll, stimulated by absorption of a high energy photon, emit a photon at a longer wavelength.

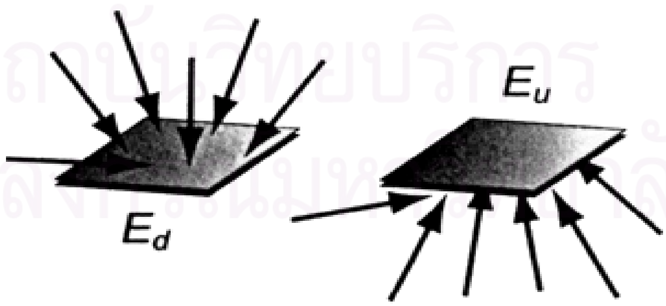

Figure 2.1 Downwelling irradiance (Ed) and upwelling irradiance (Eu) (Robinson, 2004)

Flux passing down into the lower part of the water column is described as the downwelling irradiance (Ed), whilst that which has been backscattered from below and is travelling towards the surface is the upwelling irradiance (Eu).

Basically, there are three ways in which the sea surface itself affects the light that leaves the surface in the direction of the sensor. First, the surface directly reflects sunlight and skylight. Second, there may be coloured material present at the surface which reflects the light. Third, the air-water interface refracts the light emerging from beneath the sea surface.

Intrinsic colour of the ocean is defined by spectral variations in reflectance. Sea surface reflectance (R) at any depth z is defined as:

$$R(\lambda, z) = \frac{E_u(\lambda, z)}{E_d(\lambda, z)} \tag{2.1}$$

where Eu(λ, z) is the irradiance (flux per unit surface area) in all the upward directions, or upwelling irradiance, at wavelength λ and depth z; and Ed(λ, z) is the irradiance in all the downward directions, or downwelling irradiance, at the same wavelength and depth.

In the remote sensing context, it deals with remote sensing reflectance (Rrs), which is closely related to the sea-surface reflectance R, but makes use of upwelling radiance rather than irradiance. It is a measure of how much of the downwelling light that is incident onto the sea surface. Rrs therefore provides the connection between the known input to the water body and its output which is the water-leaving radiance (L). It is defined as:

$$R_{RS}\ (\theta, \phi, \lambda, 0) = \frac{L(\theta, \phi, \lambda, 0)}{E_d(\lambda, 0)} \tag{2.2}$$

The arguments θ and ϕ on the radiance indicate that the water-leaving radiance can vary with the viewing angle (at surface, *z*=0). Remote sensing reflectance has dimensions of [sr^{-1}].

The goal of ocean colour remote sensing is to derive quantitative information on the types of substances present in the seawater and on their concentrations from variations in the spectral form and magnitude of the ocean colour signal (Figure 2.2).

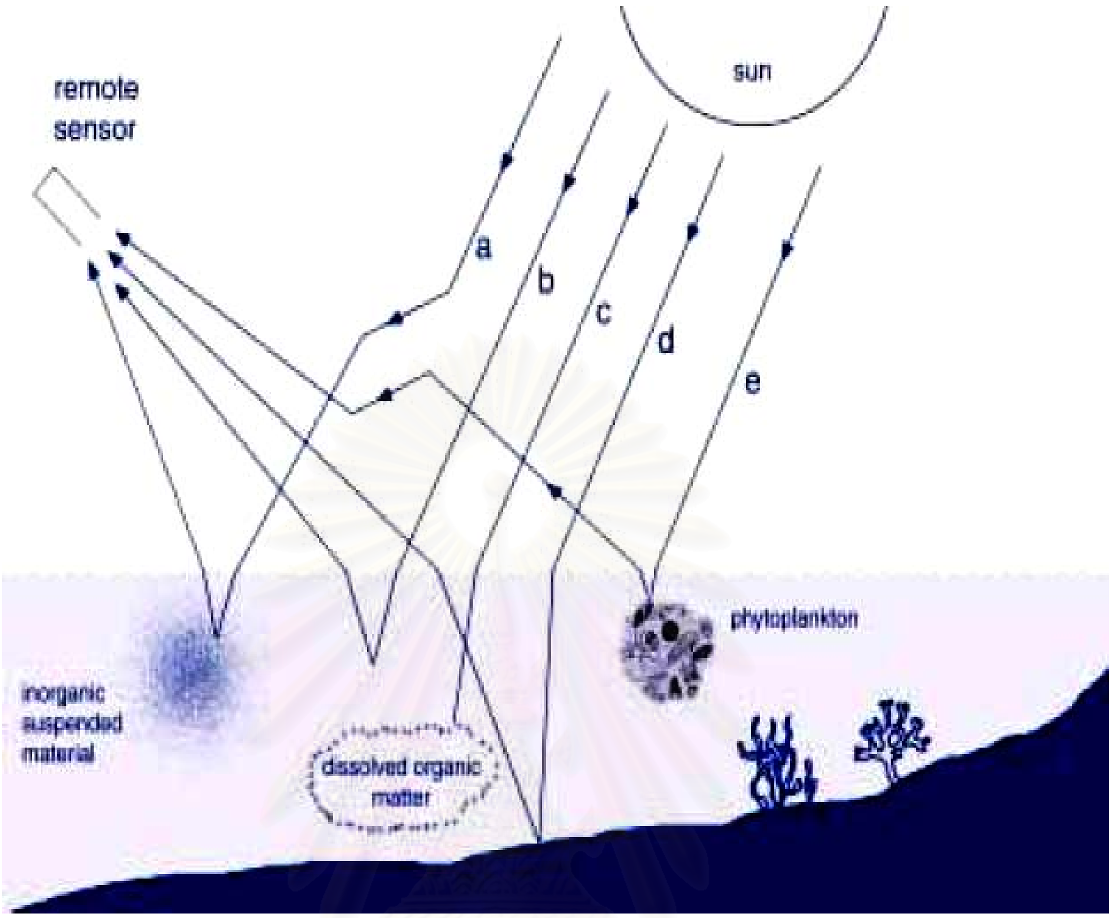

Figure 2.2 Factors that influence upwelling light leaving the sea surface. (IOCCG, 2000) (a) upward scattering by inorganic suspended material; (b) upward scattering from water molecules; (c) absorption by the coloured dissolved organic matter; (d) reflection off the bottom; and (e) upward scattering from the phytoplankton component. Note that absorption by any of these components or by the bottom will serve to decrease the water-leaving signal. Light from the sun may be scattered by atmospheric constituents before it reaches the sea surface. Similarly, light leaving the water may be scattered away from, or towards the remote sensor by the atmosphere.

It is the characteristic optical effects of oceanographically important materials such as phytoplankton pigment, suspended sediment, and organic detritus that change the appearance (brightness and colour) of the sea. This creates the potential for these water quality components to be measured by ocean colour remote sensing. Hence, the focus of ocean colour remote sensing is to recover potential information about the ocean content, carried by the light coming out of the sea.

2.3 Optical properties of seawater

Ocean colour remote sensing can be modified by the angular structure of the incident light field (Jerlov, 1976) in terms of the bulk optical properties which are conveniently divided into two mutually exclusive classes: inherent and apparent.

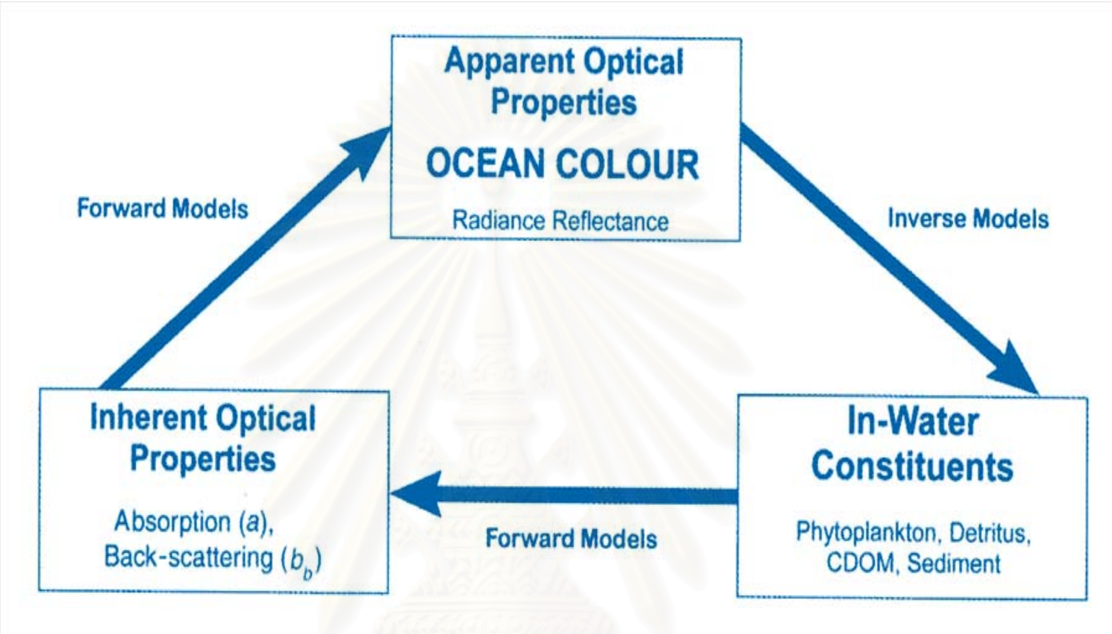

Figure 2.8 Interrelationships between the optical properties and in-water constituents (IOCCG, 2000)

2.3.1 Inherent optical properties

The inherent optical properties (IOPs) are those properties that depend only upon the medium, and therefore are independent of the ambient light field within the medium (Mobley, 1994). The two fundamental IOPs are the absorption coefficient and the volume scattering function. The IOPs, determined by both type and concentration of substances present in the water column, control the manner in which impinging photon propagate through a natural water (Bukata *et al*., 1995) and account on the processes of absorption and scattering. It is possible to compartmentalize the IOPs in terms of the different water constituents causing them (Robinson, 2004).

2.3.2 Apparent optical properties

The apparent optical properties (AOPs) are those properties that depend both on the medium and the geometric (directional) structure of the ambient light field, and that display enough regular features and stability to be useful descriptors of the water body (Mobley, 1994). Commonly used AOPs are the irradiance reflectance and the various diffuse attenuation coefficients. Due to the fact that satellite sensors cannot measure the IOPs of the sea directly, nonetheless, radiative transfer theory provides the connection between the IOPs and AOPs (Robinson, 2004).

In general, the diffuse attenuation coefficient in water refers to the ratio comparing the intensity of light at sea surface to the intensity of light at a given depth. This parameter has wide applicability in ocean optics, as it is directly related to the presence of scattering particles in the water column, either organic or inorganic. In addition, the diffuse attenuation coefficient (Kd) for downwelling irradiance is often used as an index of water clarity to compute primary production as a function of light available at depth, particularly Kd 490 as an indicator for eutrophication (IOCCG, 2000). It is defined as

$$K_d = -\frac{1}{E_d}\frac{\mathrm{d}E_d}{\mathrm{d}z} \tag{2.2}$$

where Ed (watts per square meter) is downwelling irradiance and z (in meters) is depth.

As mentioned previously, radiative transfer theory provides the connection between the IOPs and AOPs (Figure 2.8). Several rigorous studies of radiative transfer in the ocean have been undertaken to understand the relationships between ocean colour and IOPs of the water. These studies take into account the processes of absorption and scattering that control the manner in which impinging photons propagate through a natural water body. In measuring IOPs, distances are measured along the direction of the incident flux, whereas AOPs such as Kd are measured with reference to vertical intervals in the water body.

Therefore, the relationships between IOPs and AOPs typically depend on the angular distribution of the light field under which AOPs are measured. Furthermore, realistic interpretation of ocean-colour data should also take into account the natural variability in the optical signatures of these substances.

2.4 Case 1 and Case 2 waters

A bipartite classification scheme of the world ocean waters was introduced according to which all natural waters are partitioned into Case 1 and Case 2 waters (Morel and Prieur, 1977). Unlike Case 1 waters, the optical properties of Case 2 waters are influenced not only by phytoplankton pigments, but also by organic and inorganic, suspended and dissolved, materials.

Case 1 waters are basically characterized by a strong correlation between scattering and absorbing substance concentrations and the chlorophyll-*a* concentration (Robinson, 2004). The open ocean surface water is typical Case 1 water. The strong correlation is due to the fact that all the substances originate in biological processes. A primary source of the substances is photosynthesis of marine phytoplankton together with accompanying and co-varying products of their life cycles. Hence, Case 1 waters can be characterized by a single parameter—chlorophyll concentration.

Case 2 waters are characterized by a lack of any correlation between scattering and absorbing substance concentrations and chlorophyll-*a* concentration (Robinson, 2004). Accordingly, Coastal waters are often referred to as Case 2 waters. Phytoplankton is not the dominant optically active constituent. Suspended sediment and coloured dissolved organic matter, which do not always co-vary with chlorophyll-*a*, also affect seawater optical properties. Therefore, Case 2 water can be referred to as multiparameter water; its optical properties are described by a set of parameters.

However, It must be acknowledged that this classification concept is somewhat idealized because, in reality, all natural water belongs to an intermediate case (Robinson, 2004).

2.5 Optically active constituents

There are at least three in-water optically active constituents (OACs) that affect optical properties of Case 2 water. These are: phytoplankton pigments which are indexed by the chlorophyll-*a* concentration (CHLA), total suspended sediment (TSS) and coloured dissolved organic matter (CDOM) which is indexed by its absorption at a reference wavelength.

The absorption of light by pure water itself, phytoplankton pigments, suspended sediment and CDOM controls the propagation of solar radiation through the water column (Shifrin, 1988). Of these four absorbing components, water absorbs visible light primarily in the red and yellow portion of the spectrum and light of these colours is attenuated rapidly within the water column.

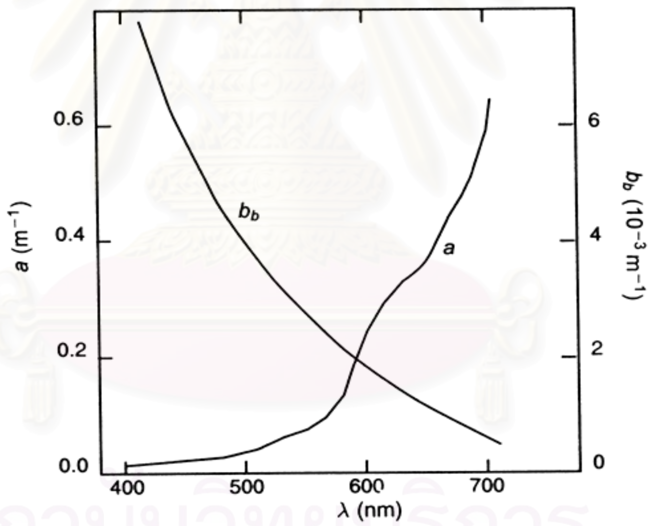

Figure 2.3 Absorption and back-scattering of pure seawater (Robinson, 2004)

The apparent colour of the sea depends on the relative concentrations of the absorbers and scatterers in the seawater. The scattering coefficient of pure seawater is high in the blue and decreases with increasing wavelength. Absorption increases with increasing wavelength so most red light is absorbed before it can be scattered out through the surface. This produces the characteristic blue appearance of pure seawater. The spectral properties of individual constituents control characteristic colour to the sea (Morel and Prieur, 1977; Mobley, 1994; Robinson, 2004).

2.5.1 Phytoplankton pigments

Water containing a population of phytoplankton has much more complex spectral characteristics due to their photosynthetic pigments. The relative amount of each pigment varies according to the species of phytoplankton. Every pigment has its own characteristic absorption spectrum (Kirk, 1994), with peaks at different wavelengths. However, it has been known that chlorophyll-a dominates in most phytoplankton species. The absorption in the live population is affected by the packaging effect of the pigments within the cells (Kirk, 1975). This, and the presence of more than one pigment, tends to broaden the absorption peaks of the natural population compared with what is observed in isolated extracted pigment samples.

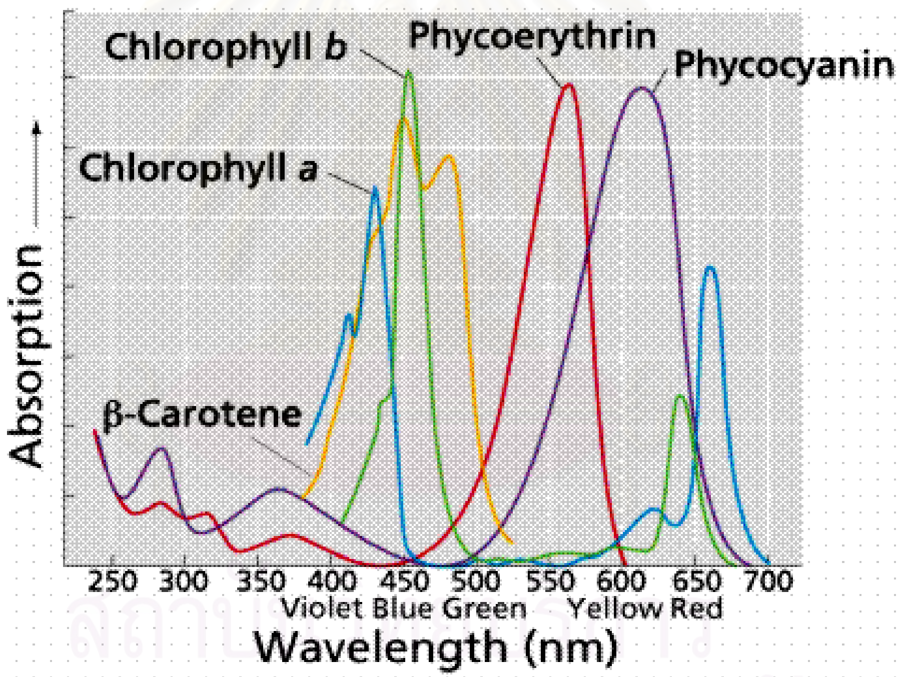

Figure 2.4 Typical spectral variation of specific absorption by various pigments (Kirk, 1994)

In general, the important wavelengths for the assessment of chlorophyll-a are in the blue (440 nm) and red (665 nm) wavebands where maximum absorption occurs, and the green wavelengths between 520 and 560 nm where reflectance is high. In addition, phytoplankton also emits about 1% of the absorbed light as fluorescence with a peak at around 685 nm.

The increased scattering as the concentration of phytoplankton increases implies that the reflectance should increase, but this is offset by increased absorption. Figure 2.5 shows typical reflectance spectra for waters in which phytoplankton dominates. The arrow indicates the way the spectrum changes with increasing chlorophyll concentration, and the dashed line is the clear water baseline spectrum.

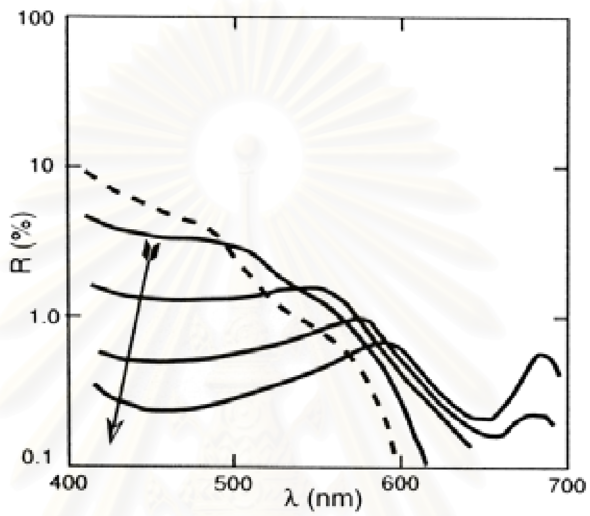

Figure 2.5 Typical reflectance spectra for seawater containing only phytoplankton. (Robinson, 2004)

The concentration of absorption and backscattering from phytoplankton tends to decrease the reflectance below the clear water spectrum at wavelengths below around 540 nm, and slightly increases it at longer wavelengths. Increasing chlorophyll content enhances this effect, with a definite minimum appearing at 440 nm caused by the chlorophyll absorption. Another minimum appears at 660 nm, although the red absorption maximum is partly masked by an apparent reflectance peak at 685 nm due to fluorescence. Although the absolute reflectance values differ greatly with different chlorophyll species, the spectral shape and its variation with chlorophyll concentration remain similar. This suggests that a chlorophyll algorithm to interpret visible wavelength radiance measurements from space should be based on spectral ratios rather than the actual magnitude of the reflectance (Robinson, 2004). It will be noticed that the reflectance does not vary very much with chlorophyll content in the 550-600 nm range of the spectrum.

2.5.2 Suspended sediment

The spectral characteristics of suspended sediments are as diverse as their composition in terms of natural material colour and size distribution, and there appears to be no consensus in the literature regarding a standard spectrum shape. The optical properties of suspended sediment are able to find evidence for natural absorption spectra, similar to yellow substance and U-shape absorption spectra with increasing absorption at both the red and blue ends (Robinson, 2004).

The optical behaviour of suspended sediment assumes that most inorganic particles do not absorb, but particles coated in a layer of organic material acquire the absorption characteristics of the organic material like CDOM. The scattering depends on the size distribution of particles. For the same concentration of suspended sediment by weight, there will be more scattering from a large population of fine particle than from a smaller number of large particles (Binding *et al.*, 2003).

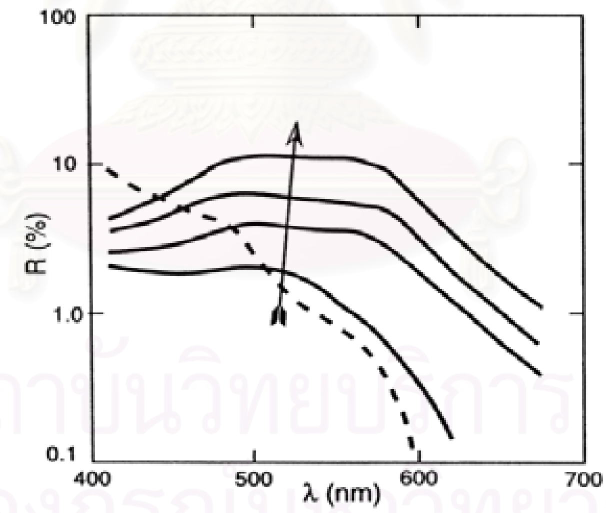

Figure 2.6 Typical reflectance spectra for sediment-dominated water (Robinson, 2004)

There is no certainty that the amount of absorption or backscatter is linearly related to the amount of suspended sediment present. Figure 2.6 shows typical reflectance spectra for coastal waters dominated by suspended sediment. The reflectance generally increases across the spectrum for increased sediment load.

2.5.3 Coloured dissolved organic matter

Coloured dissolved organic matter (CDOM), referred to in the past by various names including gelbstoff, gilvin, yellow substance or chromophoric DOM, is a group of dissolved organic materials, consisting of humic and fulvic acids (IOCCG, 2000). It has long been known to be an important component of the optical properties of coastal environments. However, an understanding of the processes regulating its influence on light availability remains largely unexplored (Siegel *et al.*, 2002).

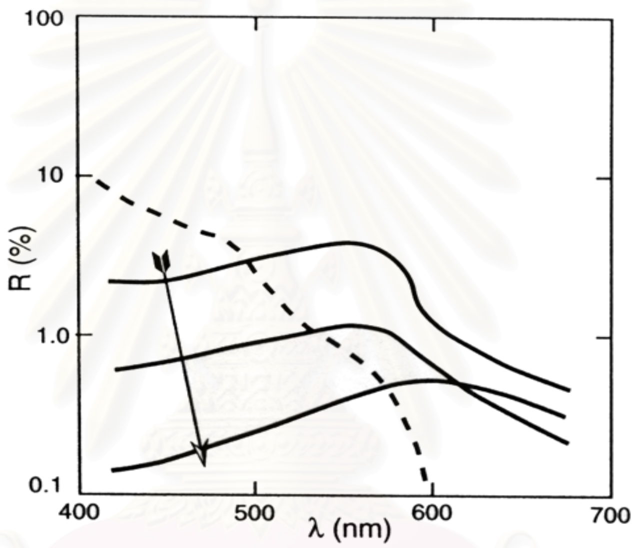

Figure 2.7 Typical reflectance spectra for yellow substance dominated water (Robinson, 2004)

CDOM may have a local origin from the degradation of phytoplankton cells and other organic particles. However, it can also be advected from a distant source (IOCCG, 2000), coming typically from land drainage through river inflows to the sea. It is therefore likely to be found in coastal waters with strong concentrations. Figure 2.7 shows typical reflectance spectra for waters in which yellow substance dominates. As for the phytoplankton spectra in Figure 2.5, increasing the concentrations of CDOM leads to increased absorption and a decrease in blue reflectance (Bricaud *et al.*, 1981). There is even the potential to use the CDOM concentration so derived as an indicator of freshwater influence in the sea, and hence an inverse measure of salinity distribution (Robinson, 2004).

CDOM can play a substantial role in the biogeochemistry of natural water merely through its influence on the aquatic light field. The magnitude of CDOM absorption varies substantially across fresh and marine water. CDOM absorbs primarily ultraviolet and is also fluorescent (Nelson and Siegel, 2002). Substantial changes in CDOM abundance itself occur due to photobleaching process (Bricaud *et al*., 1981). In coastal waters strongly influenced by river input, CDOM absorption usually dominates the total light absorption, not only in the UV-B and UV-A, but also in the blue portion of visible spectrum where phytoplankton also absorb (Blough and Vecchio, 2002).

The ratio of CDOM to phytoplankton absorption at 443 nm varies from 10 for inshore waters to about 1 approximately 100 km offshore (Nelson and Guarda, 1995; DeGrandpre *et al.,* 1996). However, although there is high correlation between chlorophyll and CDOM, the relationship is not linear (Hu *et al.,* 2003). Indeed, the input of CDOM from major rivers can have a substantial seasonal impact on the optical properties of ocean waters over significant geographical areas (Huchman *et al*., 1994).

2.6 Ocean colour algorithms

An ocean colour algorithm is a mathematical procedure for deriving water properties from the radiance measured by the satellite ocean colour sensor (Campbell, 1999). The algorithm is based on an underlying forward model of reflectance that gives water-leaving radiance as a function of water properties, including the concentrations of optically active constituents.

Algorithms may be either empirical or analytical. An empirical algorithm is based on a statistical regression derived from data. For example, in ocean colour remote sensing, this might involve a regression of the chlorophyll concentration versus a reflectance ratio. An analytical algorithm is one that is based on principles governing radiative transfer, usually expressed in terms of a theoretical model of the spectral radiance as a function of water constituents. Sometimes algorithms are called *semi*-analytical or *semi*-empirical to emphasize that no algorithms are strictly analytical (Campbell, 1999). There is always some parameterization involving statistics or data.

In the *semi*-analytical algorithm, the overall structure of the algorithm is derived from theoretical considerations but certain terms are defined based on statistical regressions. Hence, empirical approach provides a good basis in order to develop the ocean colour algorithms for coastal waters (Mishra and Rao, 2002).

The challenge is to invert this forward model in order to recover estimates of the water parameter concentrations from the satellite data (Robinson, 2004). The relationship between the concentrations of three in-water constituents and the AOPs can be determined by linear or non-linear regression analysis. When the reflectance in a band depends on more than one variable as in coastal waters, non-linear regression techniques must be used instead of a multiple linear regression which is limited for high ranges of concentration. Polynomials of a higher degree are one way of determining the complex non-linear relationship between multiple bands and concentrations of optically active constituents (IOCCG, 2004).

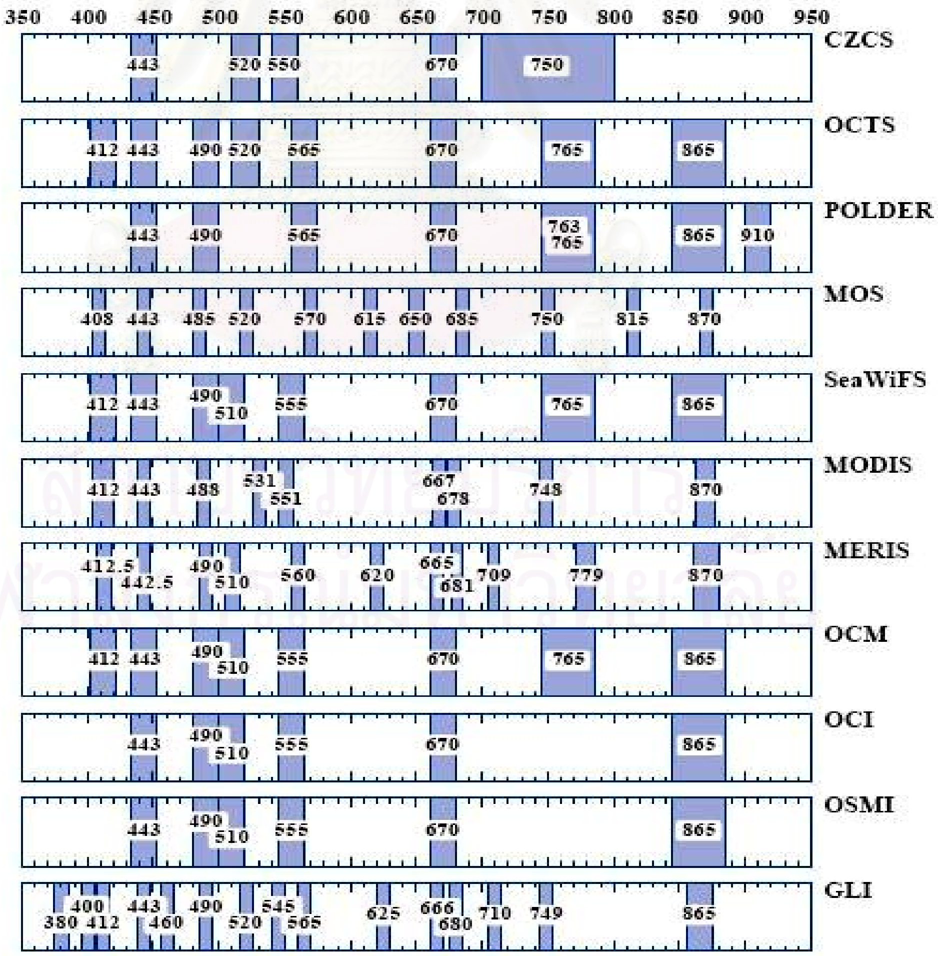

Figure 2.9 Channel positions of various ocean colour sensors (IOCCG, 1998)

For SeaWiFS algorithm (O'Reilly *et al.*, 1998), the first version of OC4 was formulated as a modified cubic polynomial in form of a third order polynomial plus an extra coefficient. However, the current version uses a fourth order polynomial with five coefficients because this yields better statistical agreement. In the same case of GLI in-water algorithm (JAXA, 2003), this single polynomial function uses the maximum band ratio determined as the greater of the reflectance values. Even at the present, MODIS algorithm (Carder *et al.*, 1999) can distinguish CDOM from chlorophyll data using band ratio at 380 and 412 nm. As it might have large errors in short wavelengths, GLI in-water algorithm (JAXA, 2003) selected band ratio at 443 and 520 nm instead. They are defined as:

$$\begin{aligned} &CHLA = 10\wedge(a_0 + a_1R + a_2R^2 + a_3R^3) + a_4 \\ &a = [0.531, -3.559, 4.488, -2.169, -0.23] \\ &R = \log_{10}(NWLR443 > NWLR460 > NWLR520)/NWLR545) \end{aligned} \tag{2.3}$$

$$\begin{aligned} &CDOM\,440 = 10\wedge(a_0 + a_1R) \\ &a = [-1.493, -1.618] \\ &R = \log_{10}(NWLR443/NWLR520) \end{aligned} \tag{2.4}$$

$$\begin{aligned} &SS = 10\wedge(a_0 + a_1R + a_2R^2) \\ &a = [-0.3186, -1.5935, 0.4376] \\ &R = \log_{10}(NWLR443/NWLR545) \end{aligned} \tag{2.5}$$

$$\begin{aligned} &Kd\,490 = 10\wedge(a_0 + a_1R + a_2R^2 + a_3R^3) \\ &a = [-0.825, -1.362, 1.094, -0.777] \\ &R = \log_{10}(NWLR460/NWLR545) \end{aligned} \tag{2.6}$$

However, the uncertainty in water-leaving radiance estimate can reduce chlorophyll concentration increase and CDOM absorption decrease, particularly in coastal waters (Sturm and Zibordi, 2002; Bulgarelli and Zibordi, 2003; Barbini *et al.*, 2003).

CHAPTER III

METHODOLOGY

3.1 Shipboard field observation

The shipboard field observations were made at totally 83 stations throughout the Upper Gulf of Thailand during 5 cruises covering the seasonal cycle in 2003-2004. Sea truth observation were surveyed using the research vessel KASETSART 1 (87 GT) which belongs to Sriracha Fisheries Research Center, Kasetsart University.

The observation plan was due in both early and late southwest and northeast monsoon seasons as shown in Table 3.1. There were 3 cruises in the southwest monsoon and 2 cruises in the northeast monsoon. In the beginning, it was designed using systematic grid sampling for locations of observed stations throughout the study area. Due to time and budget, it was necessary to adjust it to fit in those limitations. Accordingly, there were planned 17 sampling stations for each cruise observation. The positions of sampling stations are illustrated in Figure 3.1 and Table 3.2.

Table 3.1 Shipboard field observation plan

Cruise Number	Date	Season	Total Station
1	09 – 11 October 2003	late southwest monsoon	17
2	04 – 06 December 2003	early northeast monsoon	17
3	13 – 15 January 2004	late northeast monsoon	17
4	12 – 15 May 2004	early southwest monsoon	15
5	07 – 10 October 2004	late southwest monsoon	17

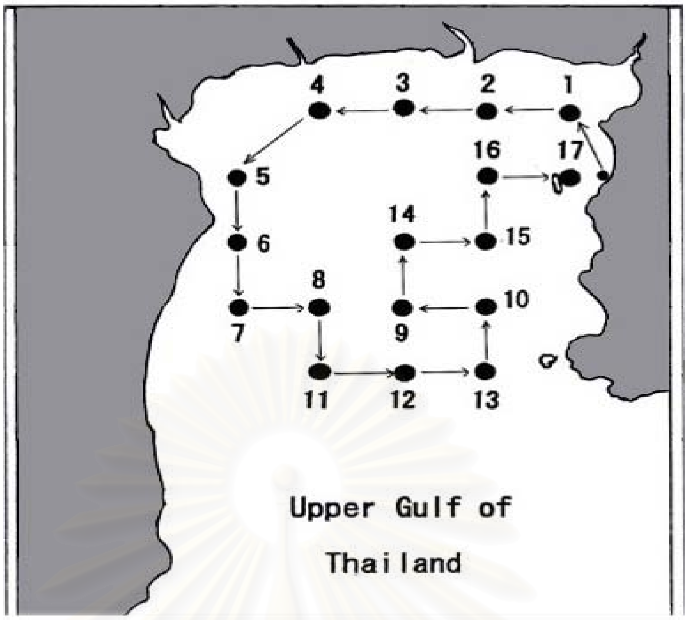

Figure 3.1 Positions of sampling stations in shipboard field observation

Table 3.2 Locations of sampling stations in shipboard field observation

Station	Latitude (N)	Longitude (E)	Depth (m)
1	13 20 00	100 50 00	14
2	13 20 00	100 40 00	17
3	13 20 00	100 30 00	11
4	13 20 00	100 20 00	8
5	13 10 00	100 10 00	15
6	13 00 00	100 10 00	15
7	12 50 00	100 10 00	15
8	12 50 00	100 20 00	22
9	12 50 00	100 30 00	22
10	12 50 00	100 40 00	27
11	12 40 00	100 20 00	26
12	12 40 00	100 30 00	22
13	12 40 00	100 40 00	40
14	13 00 00	100 30 00	15
15	13 00 00	100 40 00	19
16	13 10 00	100 40 00	20
17	13 10 00	100 50 00	10

At each station, the seawater samples were obtained at the surface layer and 5-meters depth using Vandorn Sampler, then subsequently filtered for the duplicate determinations of concentrations on three optically active constituents: chlorophyll-a, total suspended sediment and coloured dissolved organic matter. Furthermore, transparency depth and water colour level were also measured using Secchi Disc and Forel Scale, respectively.

With respect to the optical survey, the underwater light was characterized using the Profiling Reflectance Radiometer (PRR-600, Biospherical Instruments Inc.), that provides instantaneous profiles of the downwelling irradiance (Ed) and the upwelling radiance (Lu) at wavelengths coincident with the visible wavebands of satellite ocean colour sensors. The irradiance measurements at depth were normalized to the surface incident irradiance measured by a deck-based irradiance sensor (PRR-610), thus eliminating errors due to variability in the surface light conditions. Furthermore, the profiling reflectance radiometer has available seven 10-nm wavebands centred at some reference wavelengths as shown in Table 3.3.

Table 3.3 Sensor channels of the profiling reflectance radiometer (PRR-600/610)

Channel	PRR-600 Downwelling Irradiance	PRR-600 Upwelling Radiance	PRR-610 Downwelling Irradiance
412	yes	yes	yes
443	yes	yes	yes
490	yes	yes	yes
520	yes	yes	yes
565	yes	yes	yes
670	yes	yes	yes
PAR	yes	no	yes
Pressure/Depth	yes	N/A	N/A
Tilt and Roll	yes	N/A	N/A

In addition, ancillary measurements for other oceanographic parameters such data as nutrients, salinity, temperature, density, dissolved oxygen, and current were obtained using the Multiparameter Probemeter, Acoustic Dropper Current Profiler and other basic onboard oceanographic instruments.

3.2 Laboratory Techniques

3.2.1 Phytoplankton pigments

Chlorophyll-*a* concentration was measured fluorometrically following the procedures of Strickland and Parsons (1972). The water samples were filtered through GF/F Whatman glass microfibre filters (25 mm diameter, 0.7 μm pore size) under low vacuum onboard then subsequently extracted in 90% acetone at room temperature.

3.2.2 Total suspended sediment

Total suspended sediment dry weight was measured gravimetrically as outlined in Strickland and Parsons (1972). The water samples were filtered through GF/C Whatman glass microfibre filters (47 mm diameter, 1.2 μm pore size) onboard then subsequently dried at 70 °C approximately in an oven for a few hours and left in a desiccator overnight. This process was repeated until a constant weight reading is achieved.

3.2.3 Coloured dissolved organic matter

Coloured dissolved organic matter concentration was measured spectrophotometrically (Kirk, 1980). The water samples were firstly filtered through GF/F Whatman glass microfibre filters then subsequently filtered through nucleopore membrane filters (25 mm diameter, 0.2 μm pore size) for scanning the light absorption in range of 300 to 800 nanometer.

3.3 Data analysis

The optical data from the profiling reflectance radiometer for each station were analyzed and processed according to the reference wavelengths at any depths. First, the downwelling irradiance (Ed) and the upwelling radiance (Lu) were normalized by the surface incident irradiance (Es). Second, the diffuse attenuation coefficient for downwelling irradiance (Kd) was obtained. Then, the remote sensing reflectance (Rrs) was calculated from the ratio of the upwelling radiance to the downwelling irradiance. Furthermore, spline interpolation technique was used to estimate the other target wavebands in case that the PRR-600 available channels are not coincident with the wavebands of satellite ocean colour sensor.

All observed stations in each cruise were firstly categorized according to patterns of remote sensing reflectance. This method of classification is based on the relationships between the typical reflectance and the concentrations of products of interests present in the sea. Such a classification assists in the identification of relationship between each constituent and typical changes in spectral reflectance. To be clear, the patterns of remote sensing reflectance were then described according to the concentrations of three optically active constituents present.

In addition, all optically active constituents were plotted and interpolated to contour maps throughout the study area using Kriging method (Software Surfer 8.04). Kriging is a geostatistical gridding method that attempts to express trends suggested from data. Furthermore, Kriging can be either an exact or a smoothing interpolator depending on the specified parameters. It incorporates anisotropy and underlying trends in an efficient and natural manner. Consequently, their distribution patterns were basically compared with such environmental factors as salinity and nutrients. Eventually, the optical characteristics for the Upper Gulf of Thailand were described and discussed considering both spatial and temporal variations.

3.5 Algorithm development

To consider their tendencies, the in situ data on optically active constituents from all cruise stations were firstly plotted and compared with GLI in-water algorithms. In case that sensor channels of the profiling reflectance radiometer do not match up GLI ocean colour sensor channels, spline interpolation technique was used to obtain the target bands and then subsequently convert the remote sensing reflectance to the normalized water-leaving radiance.

On each optically active constituent, its in situ concentration was plotted with various band ratios or single bands. Furthermore, the best curve given highest R-square and fit in linear/nonlinear regression relationship was chosen to take more consideration. The new algorithms were constructed by the data sets from the first three cruises whilst the other two cruises were left for validation purpose. However, it should be noted that some noise data sets due to any errors in weather condition or laboratory technique might be removed. Up to this point, four in-water algorithms were eventually developed and validated for the Upper Gulf of Thailand.

CHAPTER IV

RESULTS

4.1 Distributions of optically active constituents

The sea truth data on three optically active constituents which are phytoplankton pigment, suspended sediment and coloured dissolved organic matter from all five cruises are shown in Appendix A. There were at first 17 planned stations in each cruise observation. However, some stations were necessarily cancelled due to unsuitable weather condition. Accordingly, there were totally 83 stations in 5 cruises. Those concentrations were plotted and interpolated their distributions over the area compared with such oceanographic factors as salinity and nutrients (Figure 4.1 - 4.10). Their distributions were described as follows:

The first cruise was surveyed during 9^{th}–11^{th} October 2003 represented the late southwest monsoon as illustrated in Figure 4.1 - 4.2. Salinity distribution showed large freshwater inflow from the river mouths, especially from the Mae Klong River situated at the northwest corner of the Upper Gulf. As a result, salinity increased progressively along the northwest-southeast axis with the range between 20 and 32 psu. Distribution of CDOM absorption exhibited an inverse pattern to salinity distribution whilst those of chlorophyll and suspended sediment showed high value only in the vicinity of river mouths, especially the Mae Klong River. Furthermore, Kd 490 distribution performed a similar pattern to that of chlorophyll. In addition to nutrient loadings coming along river runoff, their distributions showed different patterns with varying supplies from surface or subsurface terrestrial discharges of which rivers. For instance, distribution of phosphate at surface layer (0 m) was largely supplied from the Mae Klong and the Tha Chin Rivers whereas that of subsurface layer (5 m) was extremely transported from the Chao Phraya and the Bang Pakong Rivers. On the one hand, distribution of nitrate at surface layer was mainly supplied from the Tha Chin River whereas that of subsurface layer was largely carried on from the Bang Pakong River.

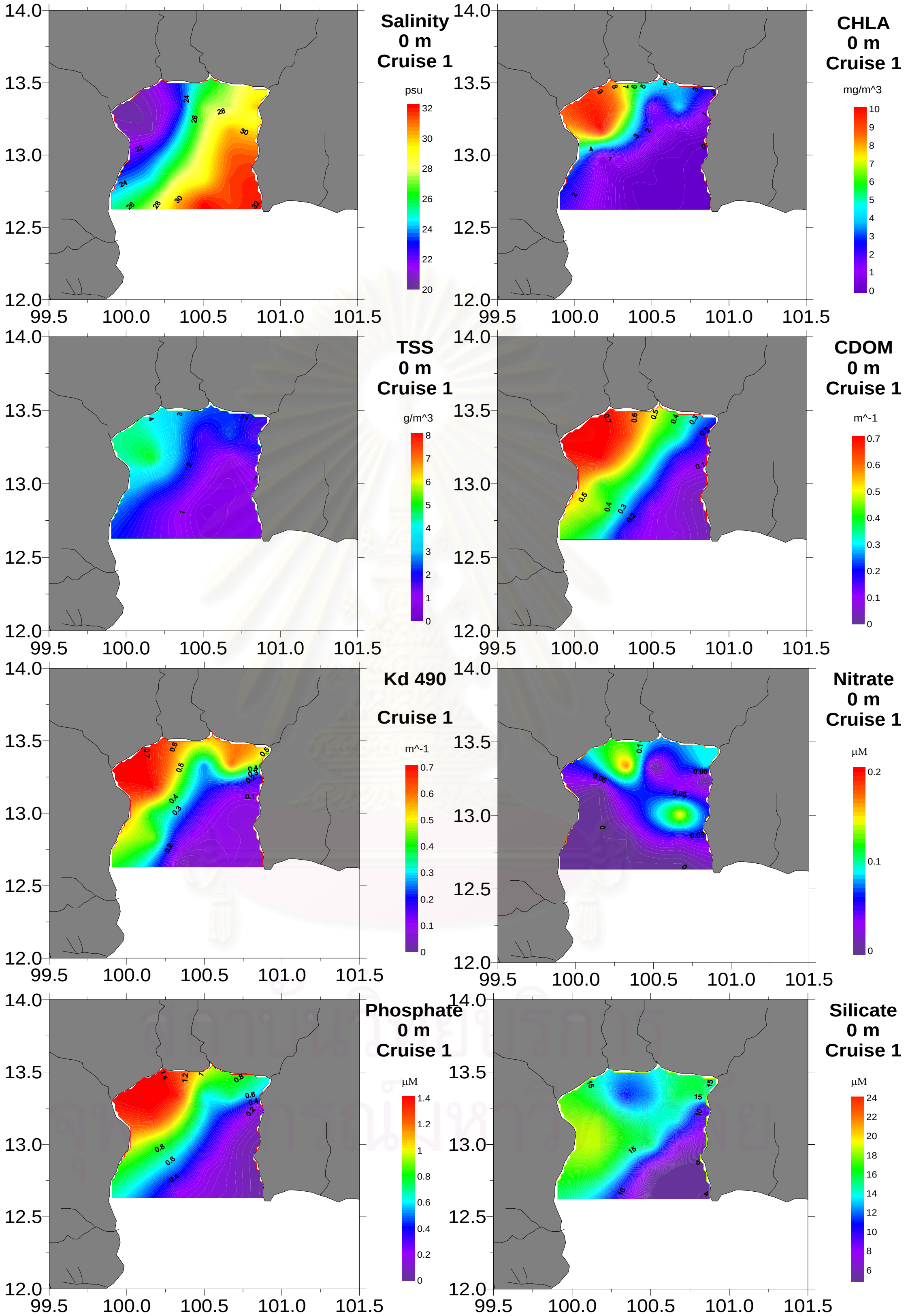

Figure 4.1 Distributions of optically active constituents, salinity, nutrients and Kd 490 at surface layer in cruise 1 (9 - 11 October 2003) by Kriging interpolation.

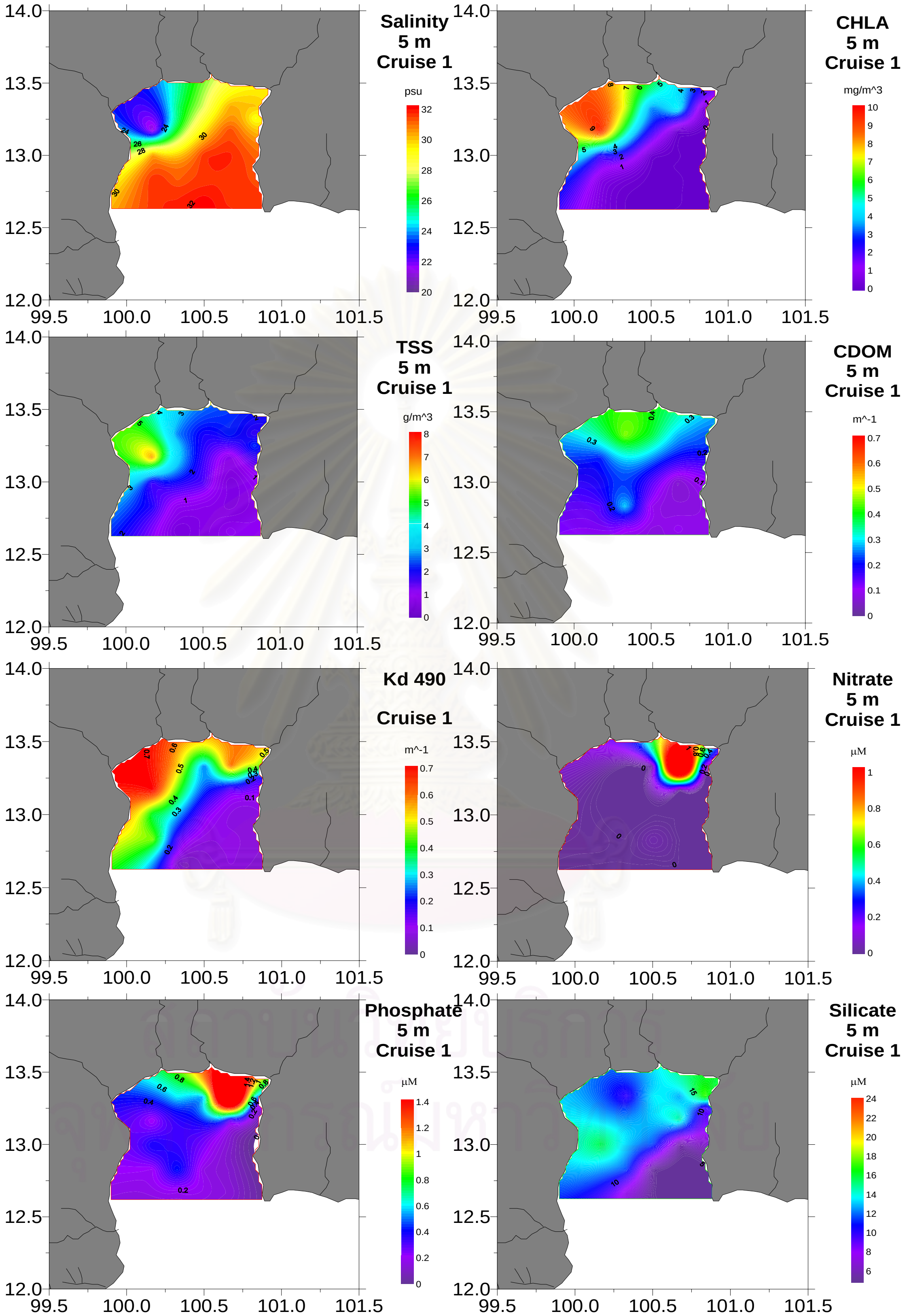

Figure 4.2 Distributions of optically active constituents, salinity, nutrients and Kd 490 at 5-meter depth in cruise 1 (9-11 October 2003) by Kriging interpolation.

The second cruise was surveyed during 4th-6th December 2003 represented the early northeast monsoon as illustrated in Figure 4.3 - 4.4. Salinity distribution still showed similar pattern to that of the first cruise. It increased progressively along the northwest-southeast axis. However, salinity was relatively higher with the range between 29 and 32 psu. Distributions of chlorophyll and total suspended sediment also exhibited similar patterns to those of the first cruise. However, distribution of total suspended sediment was relatively higher without hotspot area at the northwest corner like that in the late southwest monsoon whilst CDOM absorption was relatively lower over the area particularly from the eastern to the western part. Nevertheless, Kd490 distribution still performed a similar pattern to that of chlorophyll. In addition to nutrient loadings, distribution of nitrate at surface layer was extremely supplied from the Tha Chin and the Bang Pakong Rivers whereas that of subsurface layer was largely found along the coast near the Phak Bia Cape. On the other hand, those of phosphate and silicate at both surface and subsurface were mainly supplied from the coast of the Phak Bia Cape.

The third cruise was surveyed during 13th-15th January 2004 represented the late northeast monsoon as illustrated in Figure 4.5 - 4.6. Salinity distribution still increased progressively along the northwest-southeast axis with the range between 29 and 32 psu. However, distribution of chlorophyll concentration and CDOM absorption were relatively lower over the whole area of the Upper Gulf with a slight increase at the northwest corner from the Tha Chin River Mouth to the Phak Bia Cape. In contrast, distribution of total suspended sediment showed extremely high value in the vicinity of the Tha Chin and the Bang Pakong River Mouths. Furthermore, Kd490 exhibited a similar distribution pattern to that of total suspended sediment. In addition to nutrient loadings, distributions of nitrate, phosphate and silicate showed their highest points in the adjacent areas of the Phak Bia Cape.

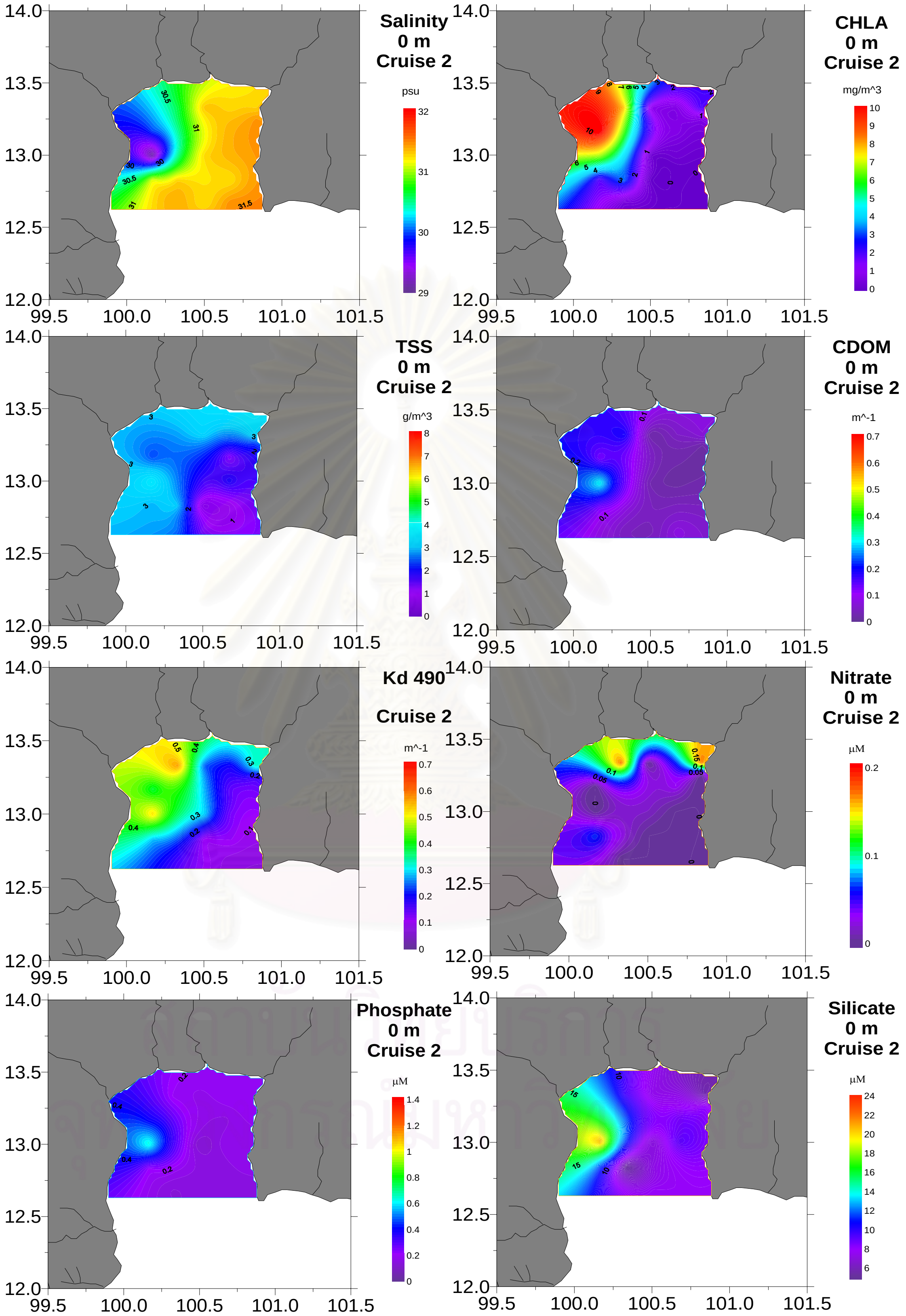

Figure 4.3 Distributions of optically active constituents, salinity, nutrients and Kd 490 at surface layer in cruise 2 (4-6 December 2003) by Kriging interpolation.

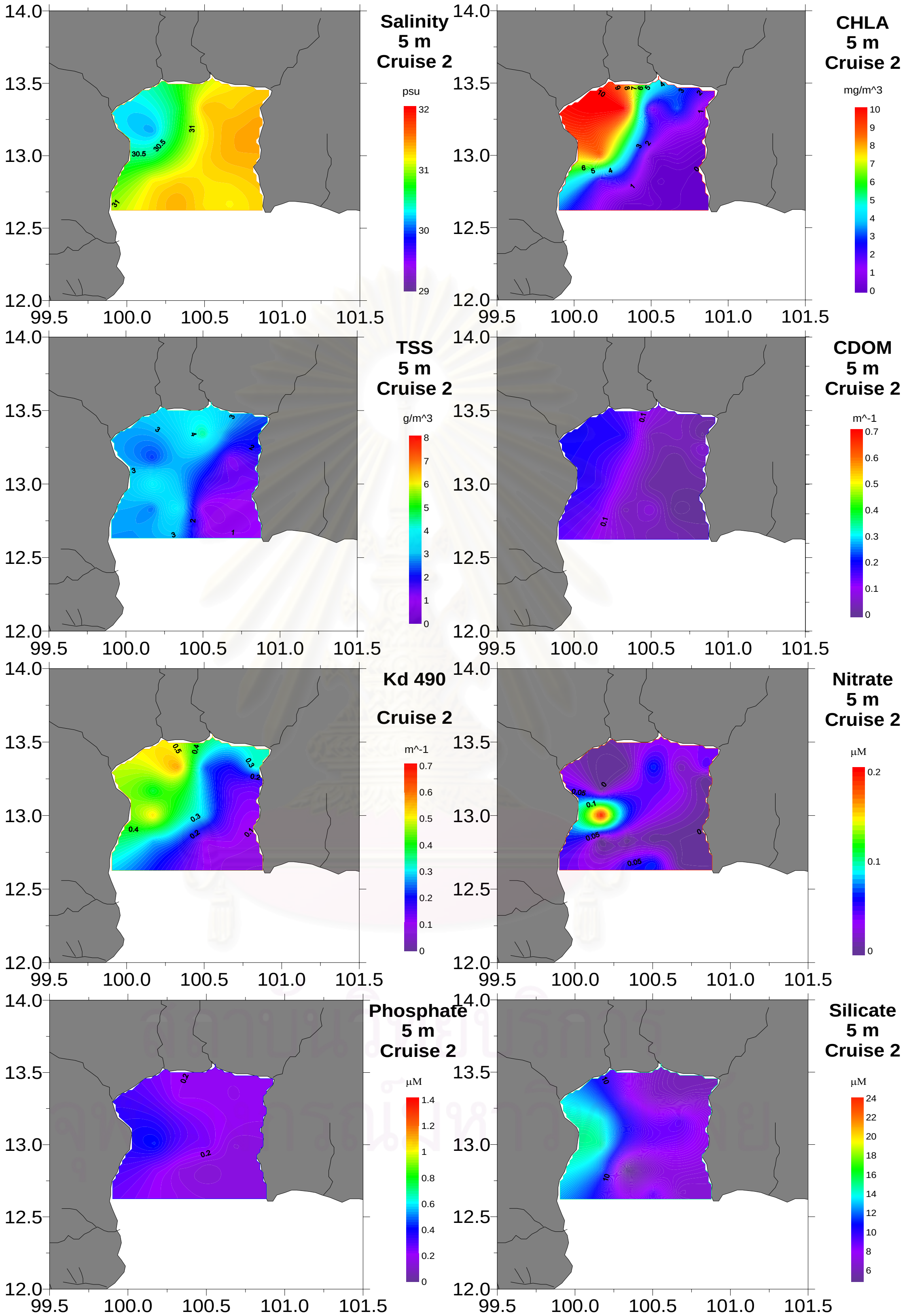

Figure 4.4 Distributions of optically active constituents, salinity, nutrients and Kd 490 at 5-meter depth in cruise 2 (4-6 December 2003) by Kriging interpolation.

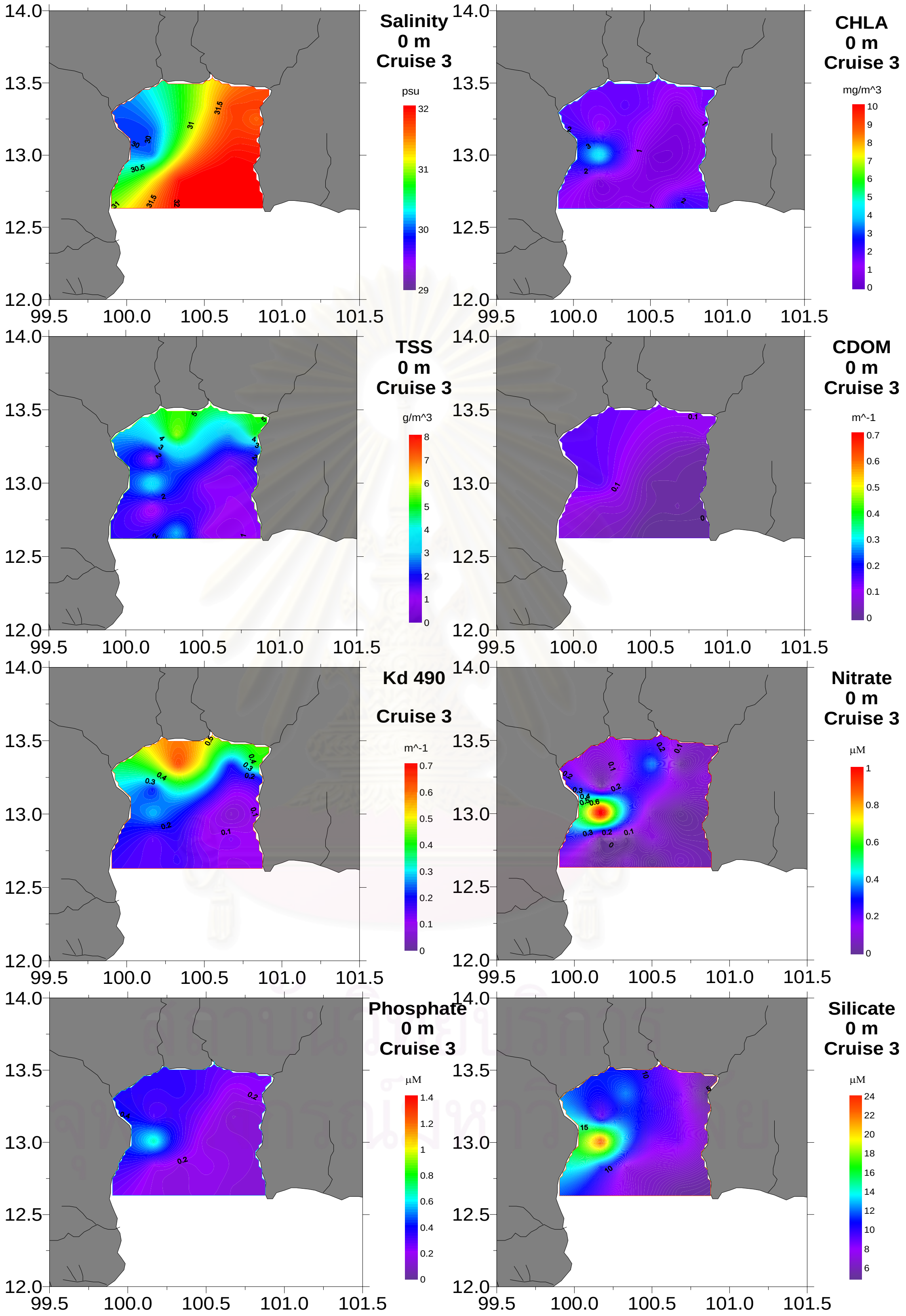

Figure 4.5 Distributions of optically active constituents, salinity, nutrients and Kd 490 at surface layer in cruise 3 (13-15 January 2004) by Kriging interpolation.

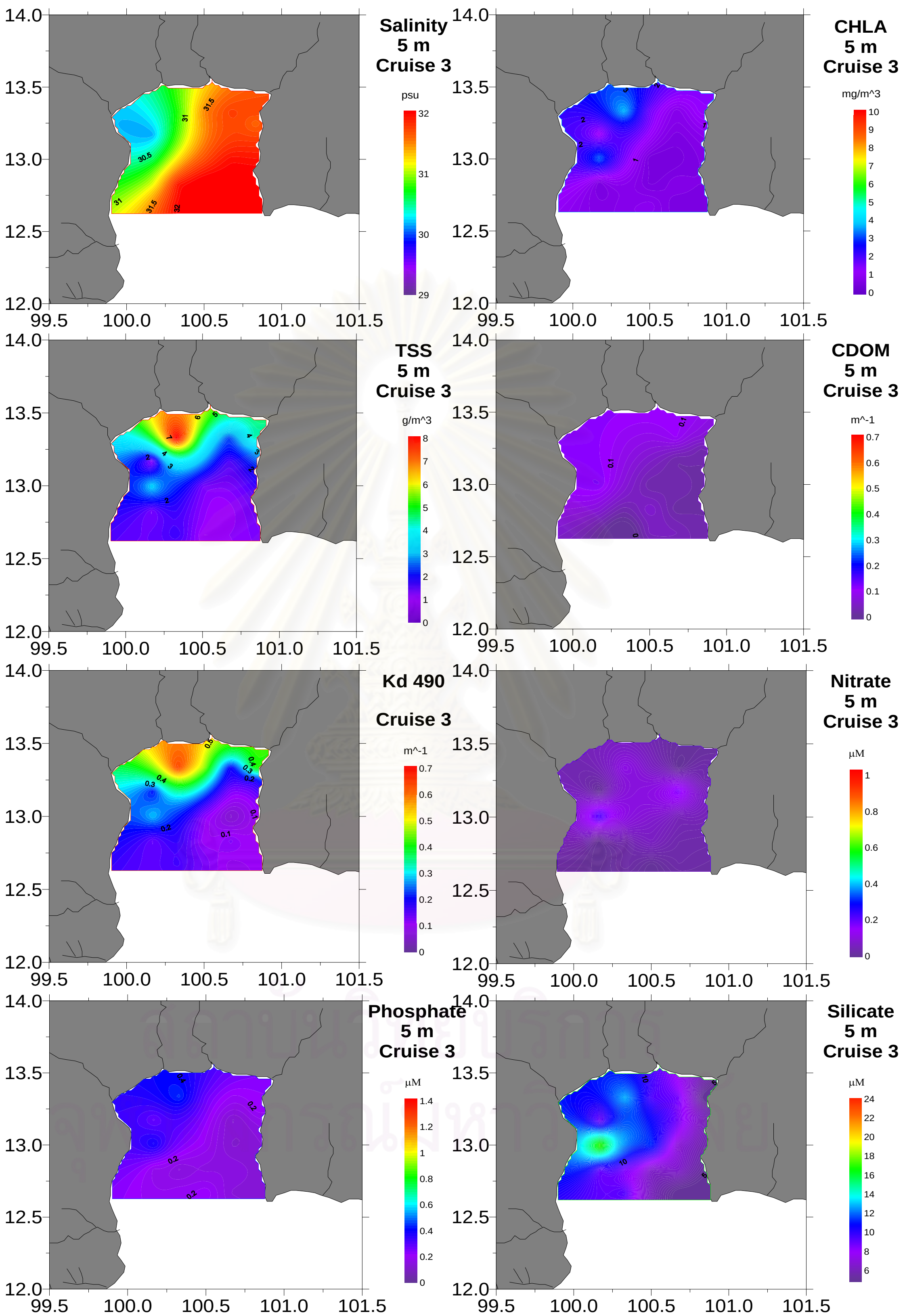

Figure 4.6 Distributions of optically active constituents, salinity, nutrients and Kd 490 at 5-meter depth in cruise 3 (13-15 January 2004) by Kriging interpolation.

The forth cruise was surveyed during 12th-15th May 2004 represented the early southwest monsoon as illustrated in Figure 4.7 - 4.8. Salinity distribution showed slight freshwater inflow from the river mouths, especially from the Chao Phraya River situated at the central north of the Upper Gulf. As a result, salinity increased downwards with the range between 30 and 33 psu. Distribution of CDOM absorption performed an inverse pattern to salinity distribution whilst that of total suspended sediment showed relatively low value with some higher peaks in the adjacent areas near the Bang Pakong River Mouth and the Phak Bia Cape. In contrast, distribution of chlorophyll showed relatively higher value than that in the northeast monsoon with some highest points in the surrounding areas of the Chao Phraya and the Bang Pakong River Mouths and the Phak Bia Cape. Furthermore, Kd490 distribution performed a similar pattern to that of chlorophyll. In addition to nutrient loadings, distributions of nitrate and phosphate were largely supplied from the Bang Pakong River whereas that of silicate exhibited large amount in the vicinity of river months and decreased downwards.

The fifth cruise was surveyed during 7th-10th October 2004 represented the late southwest monsoon as illustrated in Figure 4.9 - 4.10. Salinity distribution showed similar pattern to that of the first cruise which was the same monsoon season. Salinity increased progressively along the northwest-southeast axis with the range between 22 and 33 psu. Accordingly, distribution of CDOM absorption exhibited an inverse pattern to that of salinity whilst distribution of total suspended sediment showed large amount in the adjacent areas of the river mouths and performed similar pattern to those in the first and second cruises. Contrary to that of total suspended sediment, distribution of chlorophyll was relatively lower over the whole area of the Upper Gulf. However, Kd490 distribution exhibited a similar pattern to that of total suspended sediment. In addition to nutrient loadings, distributions of nitrate and silicate were largely supplied from the Chao Phraya River. On the other hand, distribution of phosphate showed high value at the northwest corner of the Upper Gulf and exhibited a similar pattern to that of CDOM absorption.

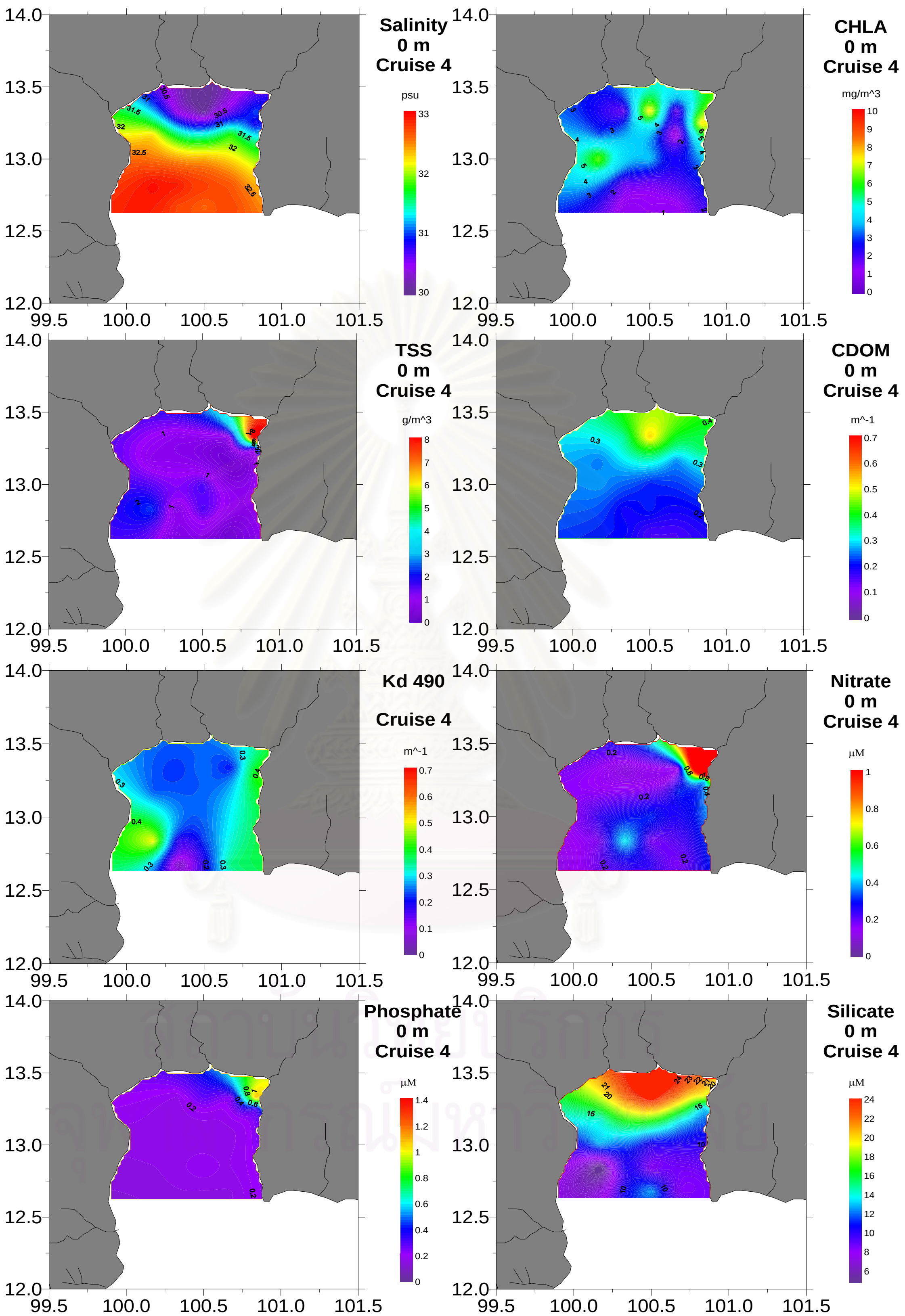

Figure 4.7 Distributions of optically active constituents, salinity, nutrients and Kd 490 at surface layer in cruise 4 (12 - 15 May 2004) by Kriging interpolation.

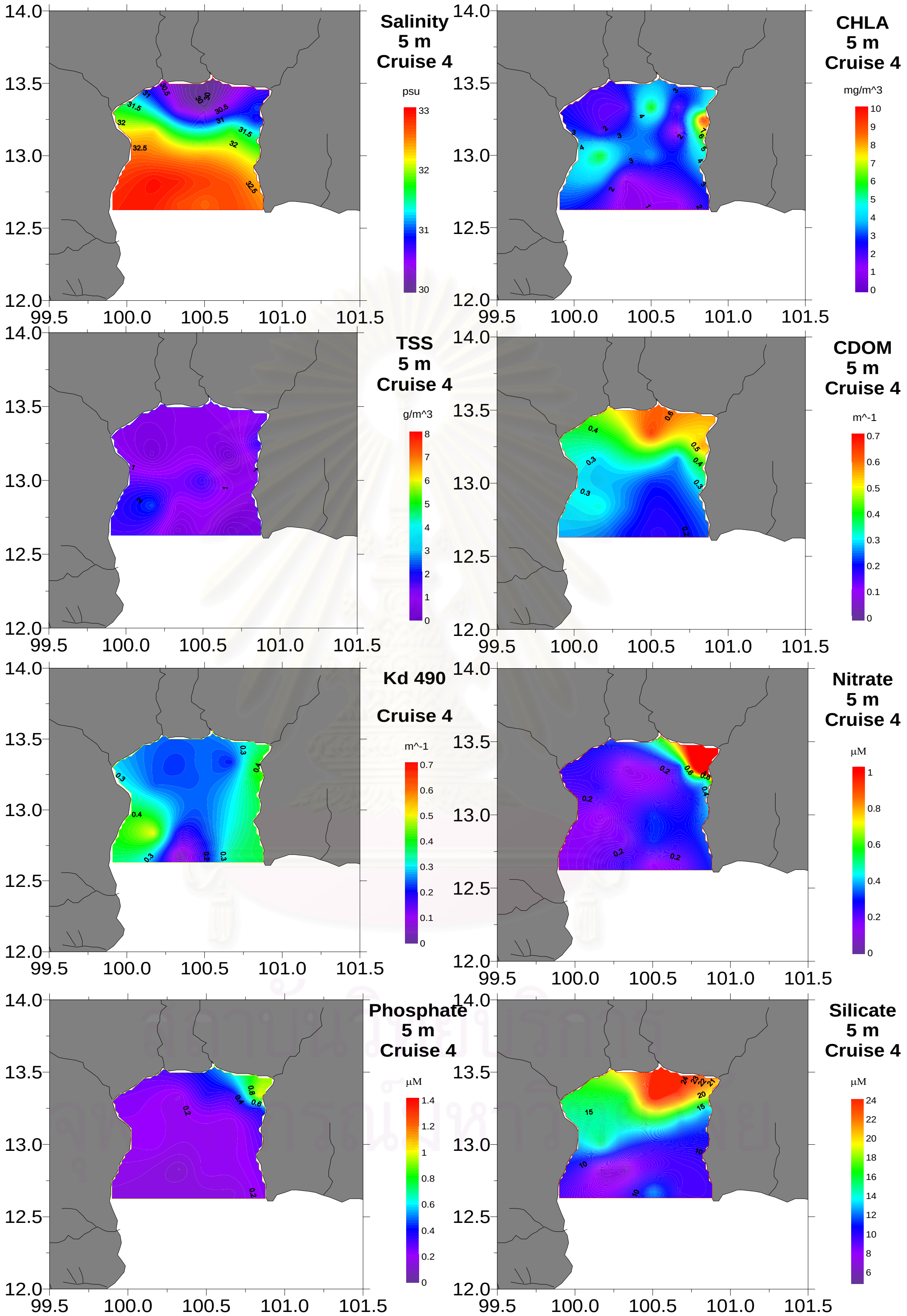

Figure 4.8 Distributions of optically active constituents, salinity, nutrients and Kd 490 at 5-meter depth in cruise 4 (12 - 15 May 2004) by Kriging interpolation.

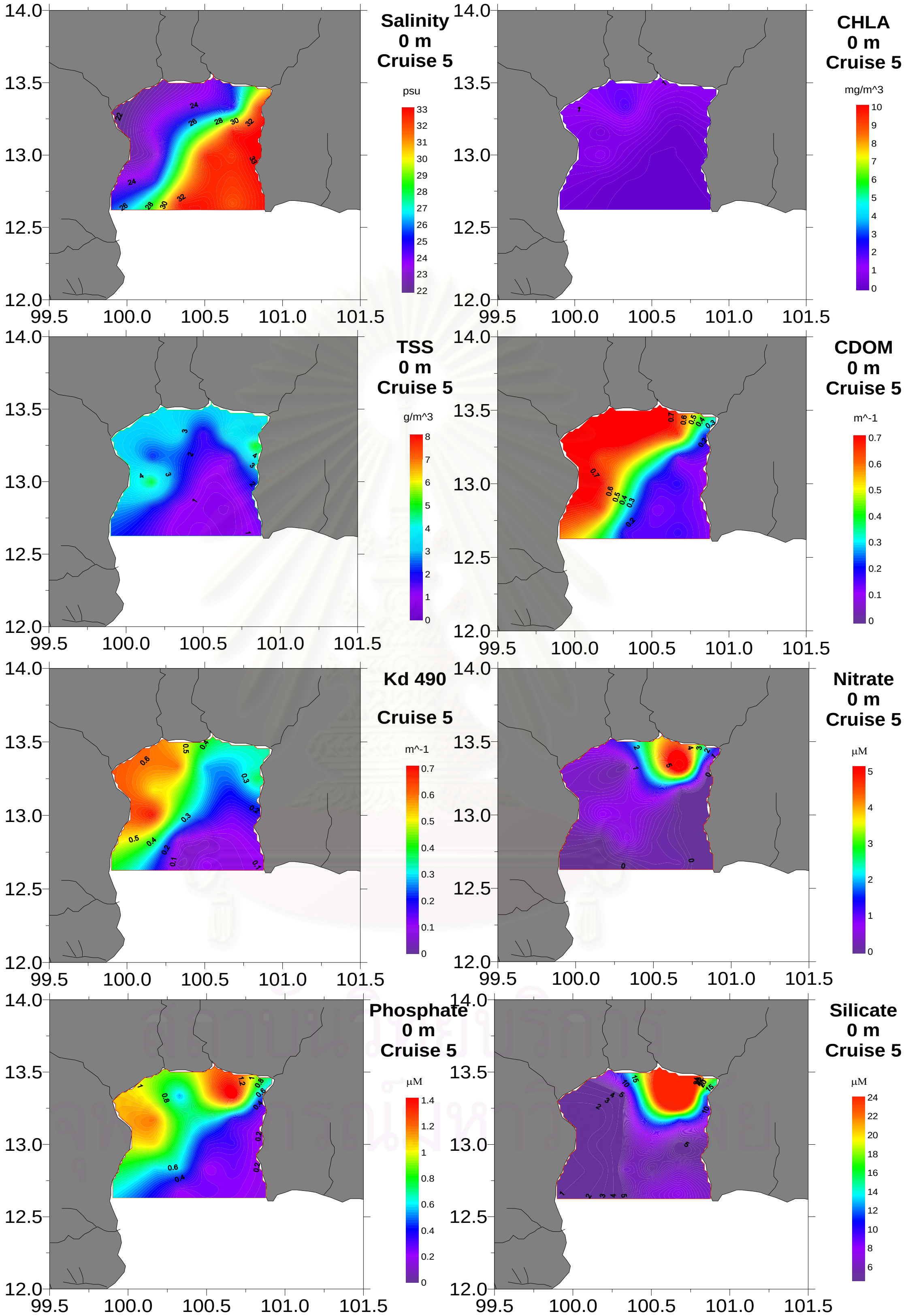

Figure 4.9 Distributions of optically active constituents, salinity, nutrients and Kd 490 at surface layer in cruise 5 (7 - 10 October 2004) by Kriging interpolation.

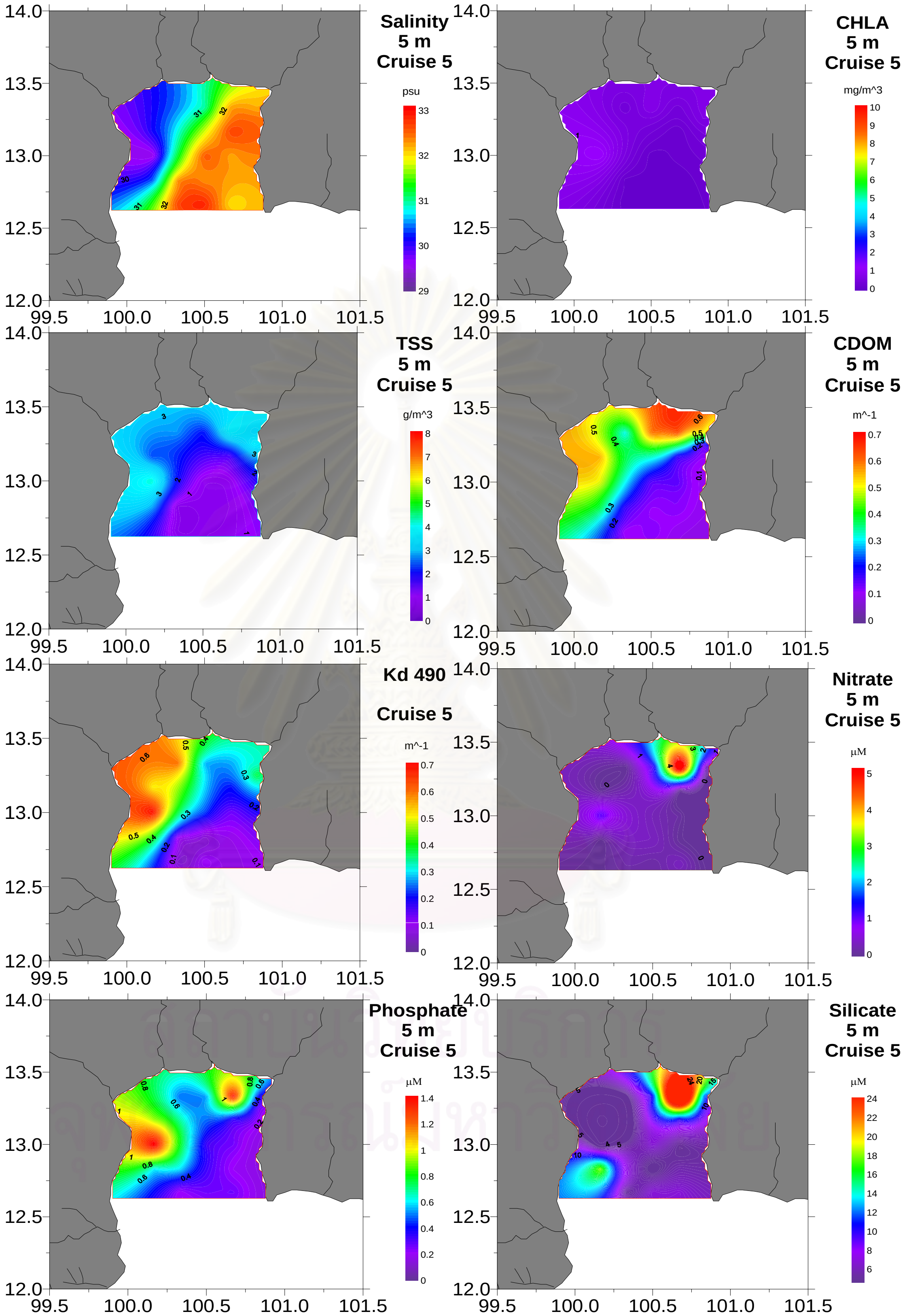

Figure 4.10 Distributions of optically active constituents, salinity, nutrients and Kd 490 at 5-meter depth in cruise 5 (7-10 October 2004) by Kriging interpolation.

4.2 Patterns of remote sensing reflectance

The optical data from the profiling reflectance radiometer were processed to obtain the downwelling irradiance (Ed) and the upwelling radiance (Lu). Consequently, the remote sensing reflectance (Rrs) and the diffuse attenuation coefficient (Kd) for downwelling irradiance at wavelength 490 nm were calculated as shown in Appendix B. The spectrum distributions of remote sensing reflectance show the optical water type characterizing by the concentrations of three optically active constituents which are: phytoplankton pigment, suspended sediment and coloured dissolved organic matter. As indicated by theory, the remote sensing reflectance is a result of composition between absorption and scattering. It is obvious that high remote sensing reflectance means high scattering and low absorption. Patterns of remote sensing reflectance in each cruise observation were described as follows.

In the first cruise, patterns of remote sensing reflectance exhibited distinct characterization of three different optical groups as shown in Figure 4.11- 4.12. The first group showed large absorption in short wavelengths (blue wavebands) and large reflectance in long wavelengths (green wavebands) which coincided with those stations situated in the adjacent areas of river mouths where relatively high chlorophyll concentration, CDOM absorption and suspended sediment were observed (Figure 4.12a). The second group showed relatively small absorption in short wavelengths and relatively small reflectance in long wavelengths which coincided with those stations located in the southeast corner of the Upper Gulf where relatively lower chlorophyll a concentration, CDOM absorption and suspended sediment were observed (Figure 4.12b). The last group exhibited moderate absorption in short wavelengths and moderate reflectance in long wavelengths which coincided with those stations along the NE-SW axis which separated the first two areas (Figure 4.12c).

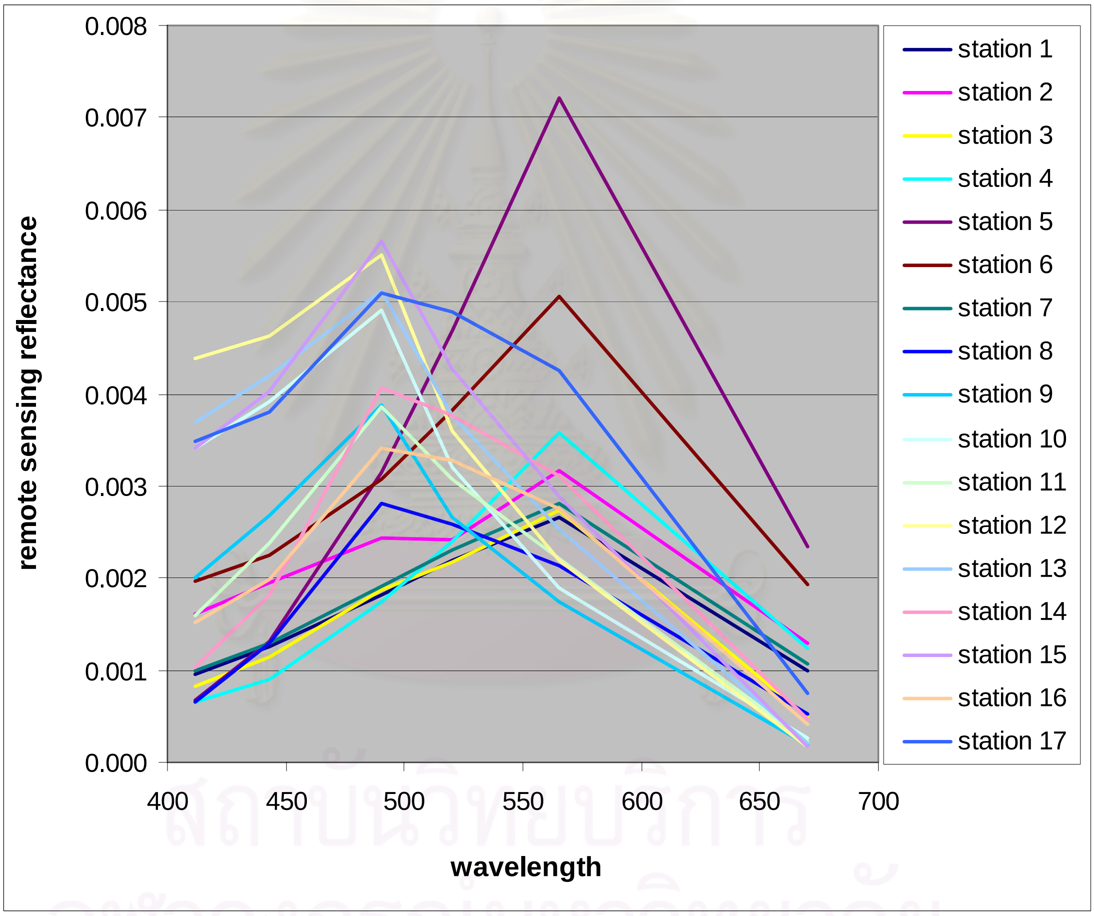

Figure 4.11 Remote sensing reflectance for all stations in cruise 1

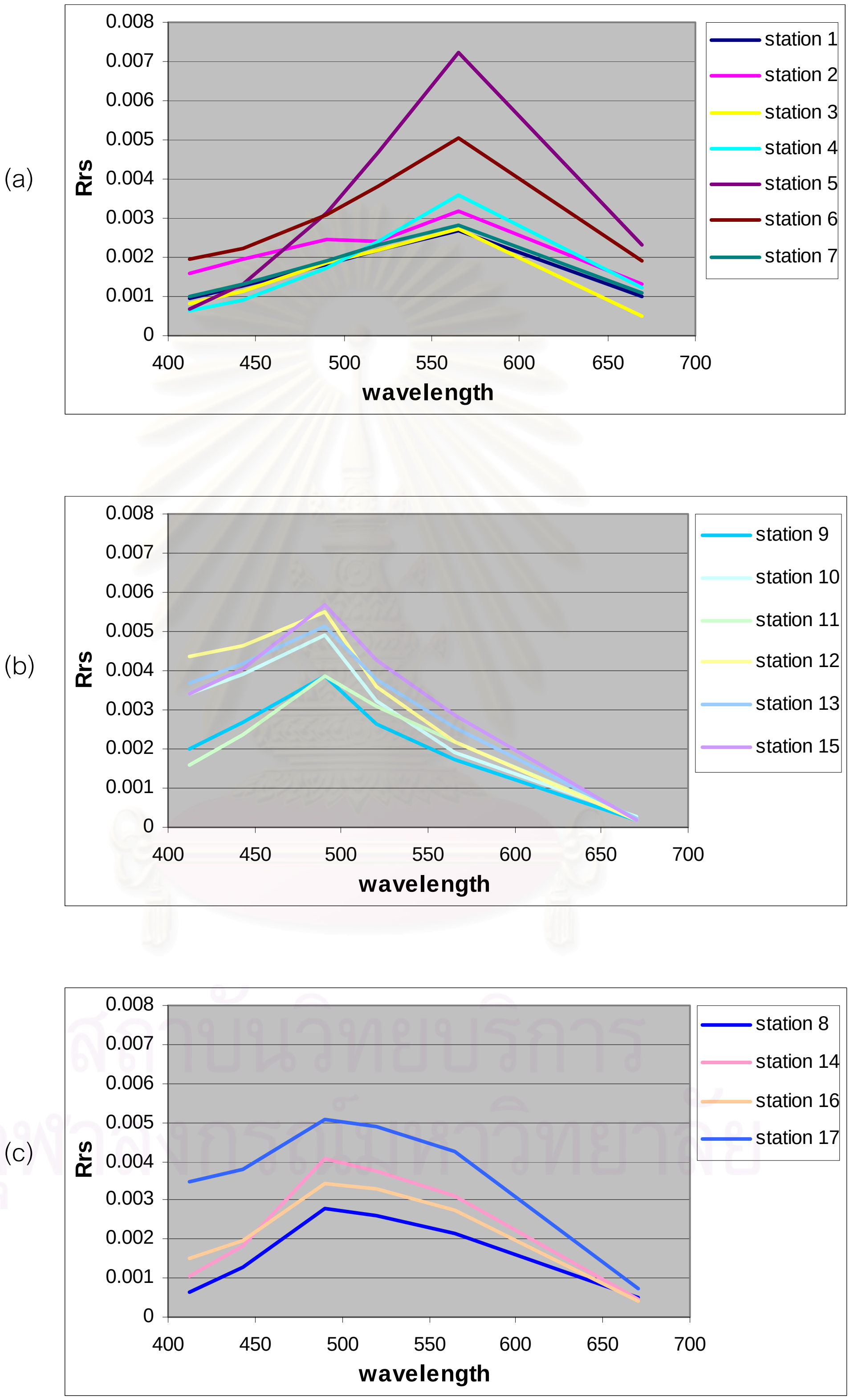

Figure 4.12 Patterns of remote sensing reflectance for cruise 1

In the second cruise, patterns of remote sensing reflectance exhibited distinct characterization of three different optical groups as shown in Figure 4.13 - 4.14. The first group showed large absorption in short wavelengths and large reflectance in long wavelengths which coincided with those stations situated in the northwest corner of the Upper Gulf where relatively high chlorophyll concentration, CDOM absorption and suspended sediment were observed (Figure 4.14a). The second group showed relatively small absorption in short wavelengths and relatively small reflectance in long wavelengths which coincided with those stations located in the southeast corner of the Upper Gulf where relatively lower chlorophyll concentration, CDOM absorption and suspended sediment were observed (Figure 4.14b). The last group exhibited relatively small absorption in short wavelengths and relatively large reflectance in long wavelengths which coincided with those stations in the southwest and northeast corners of the Upper Gulf where relatively moderate chlorophyll concentration and relatively high suspended sediment were observed (Figure 4.14c).

In the third cruise, patterns of remote sensing reflectance exhibited distinct characterization of four different optical groups as shown in Figure 4.15 - 4.16. The first group showed large reflectance in both short and long wavelengths which coincided with those stations situated in the adjacent areas of river mouths where relatively high suspended sediment were observed (Figure 4.16a). The second group showed relatively small reflectance in both short and long wavelengths which coincided with those stations located in the northwest corner of the Upper Gulf where moderate chlorophyll a concentration, CDOM absorption and suspended sediment were observed (Figure 4.12b). The third group exhibited relatively small absorption in short wavelengths and moderate reflectance in long wavelengths which those stations where moderate chlorophyll concentration and suspended sediment were observed (Figure 4.12c). The last group exhibited relatively small absorption in short wavelengths and relatively small reflectance in long wavelengths which coincided with those stations in the southeast corner of the Upper Gulf where relatively low chlorophyll concentration and suspended sediment were observed (Figure 4.12d).

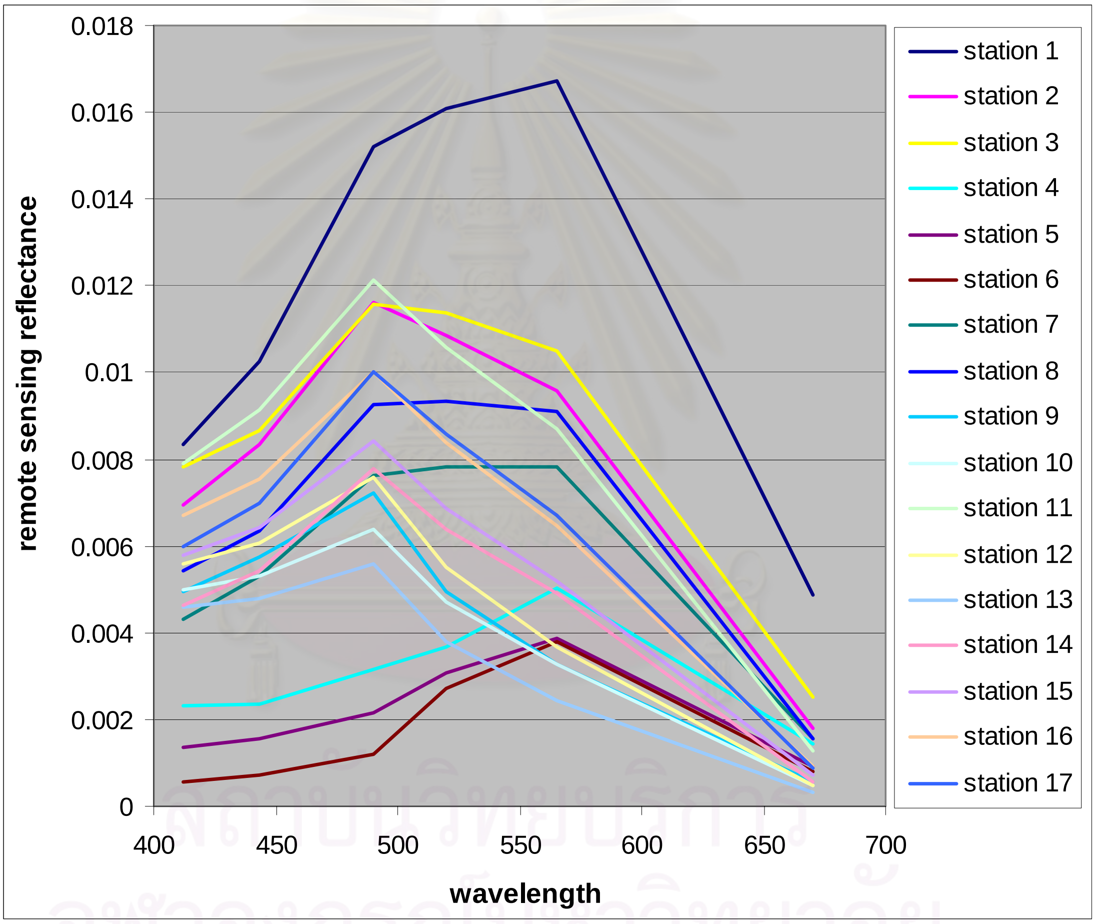

Figure 4.13 Remote sensing reflectance for all stations in cruise 2

(a)

(b)

(c)

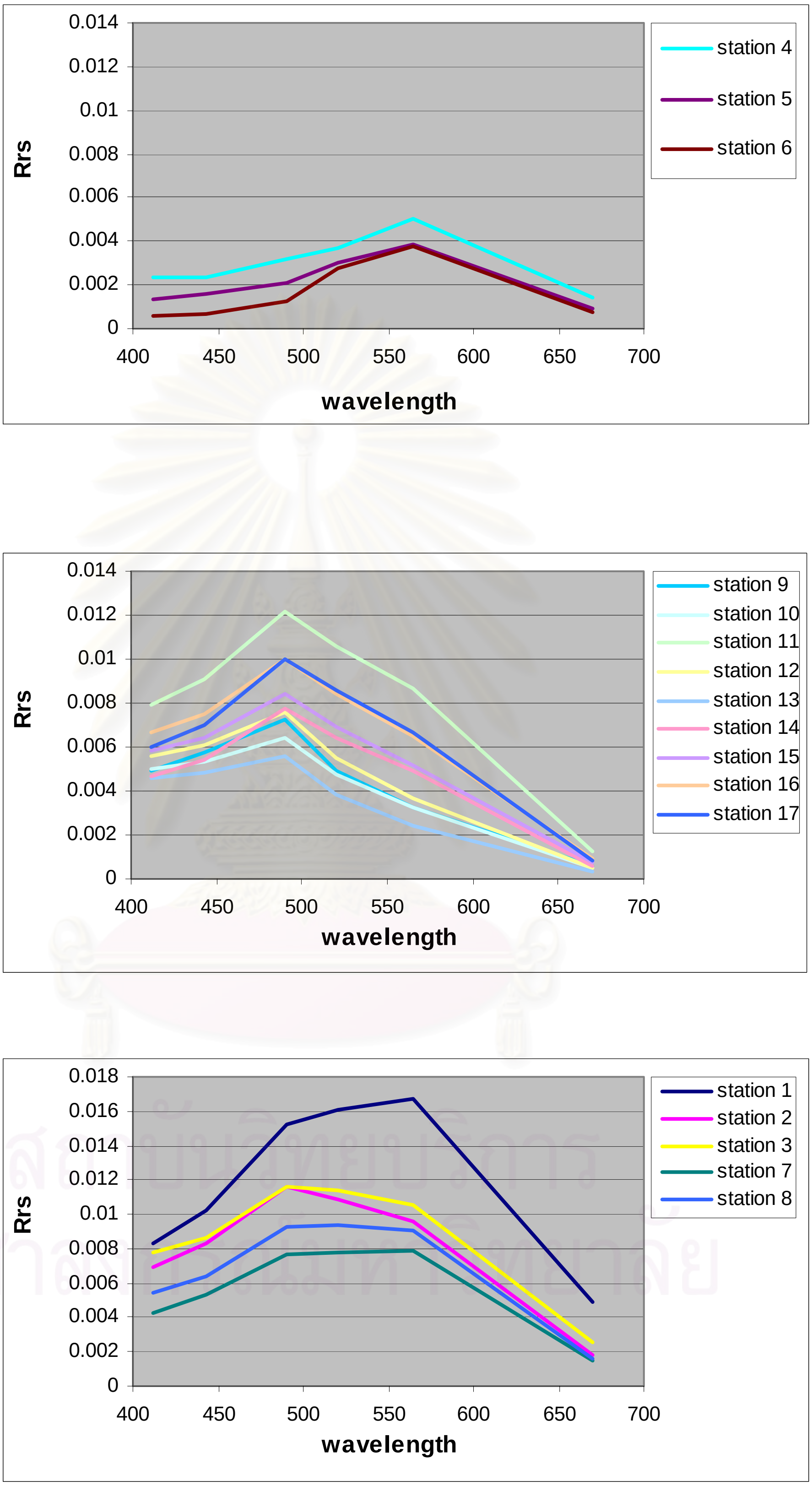

Figure 4.14 Patterns of remote sensing reflectance for cruise 2

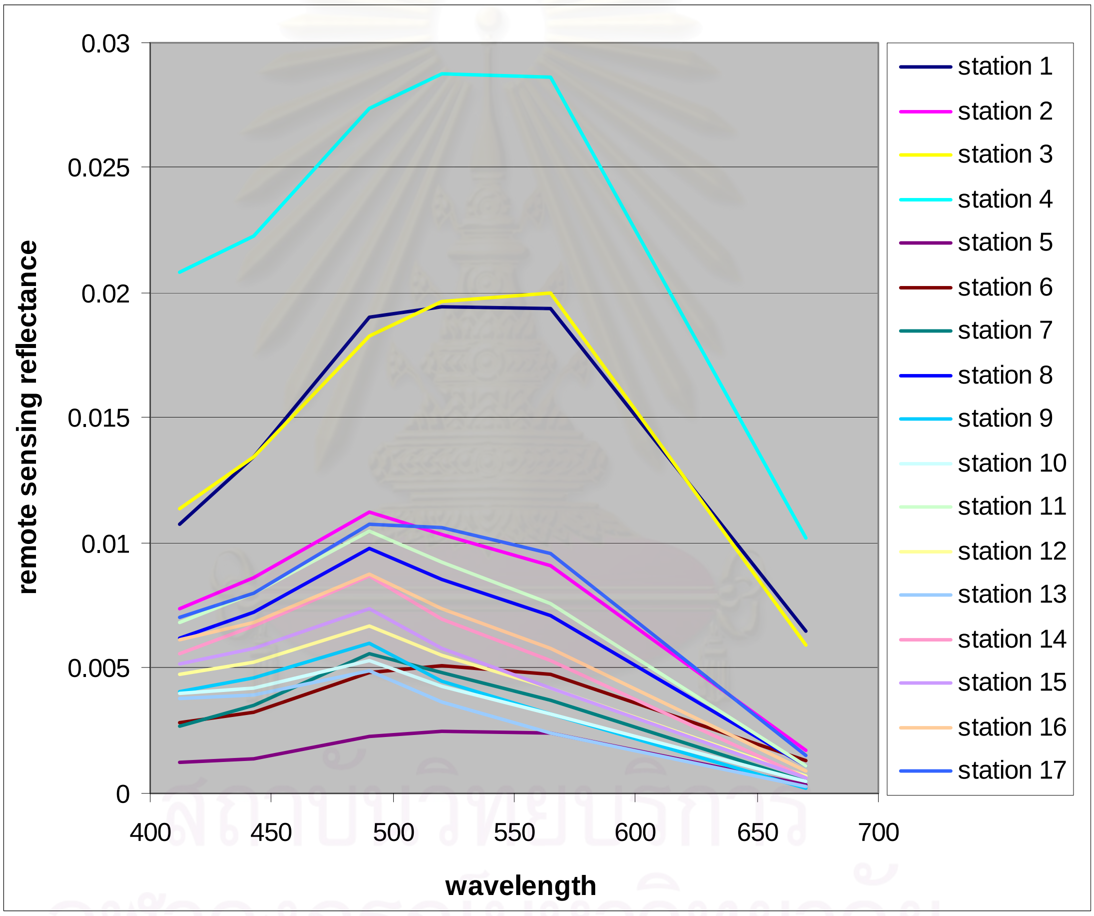

Figure 4.15 Remote sensing reflectance for all stations in cruise 3

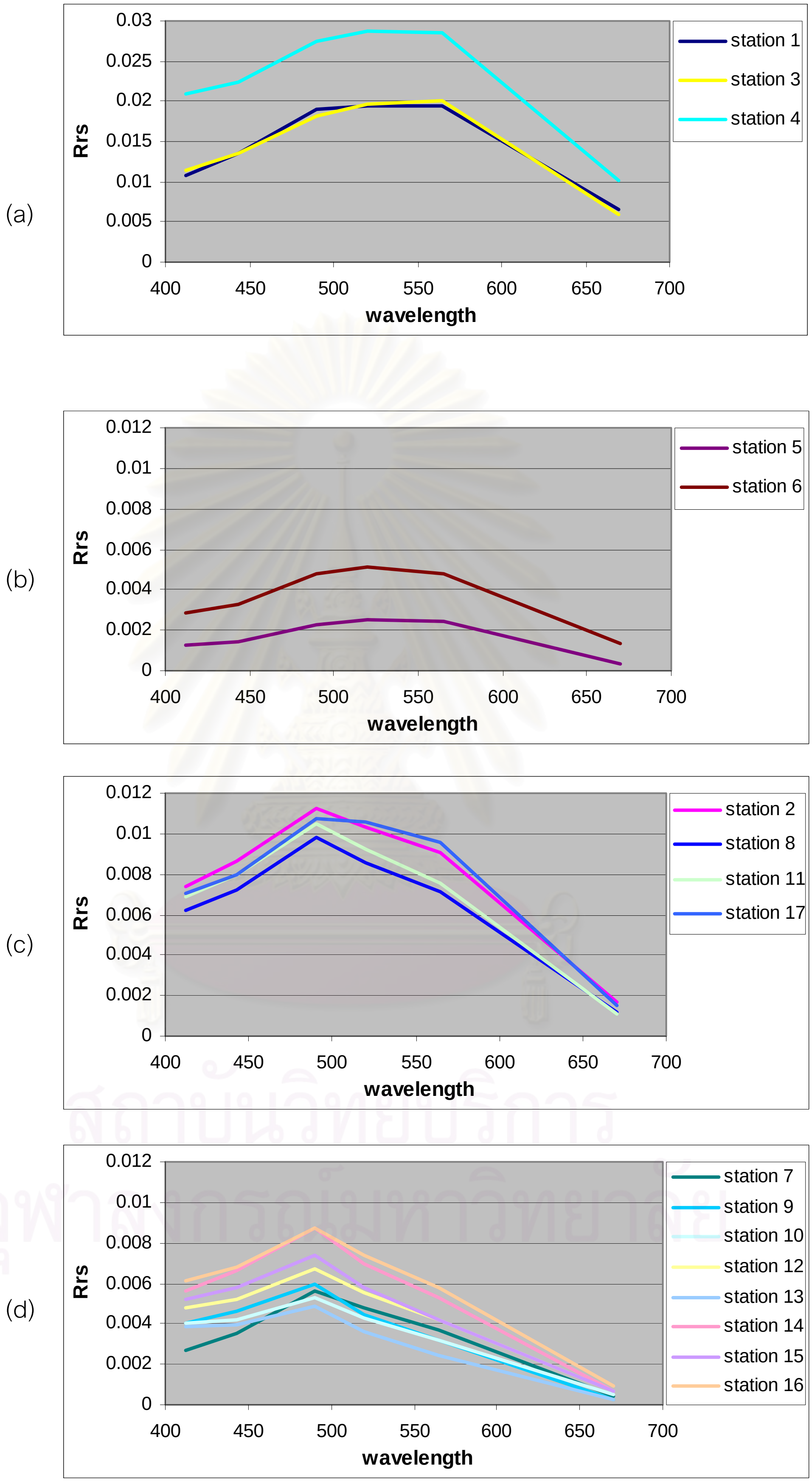

Figure 4.16 Patterns of remote sensing reflectance for cruise 3

In the forth cruise, patterns of remote sensing reflectance also exhibited distinct characterization of four different optical groups as shown in Figure 4.17 - 4.18. The first group showed large absorption in short wavelengths and relatively large reflectance in long wavelengths which coincided with those stations situated in the vicinity of river mouths where high CDOM absorption was observed (Figure 4.18a). The second group showed large reflectance in both short and long wavelengths which coincided with those stations located in the northeast and southwest corners of the Upper Gulf where high chlorophyll concentration and moderate suspended sediment were observed (Figure 4.18b). The third group exhibited small absorption in short wavelengths and relatively small reflectance in long wavelengths which those stations where low concentrations of chlorophyll and suspended sediment were observed (Figure 4.18c). The last group exhibited extremely small absorption in short wavelengths and relatively large reflectance in long wavelengths which coincided with those stations in the middle of the Upper Gulf where moderate concentrations of chlorophyll and suspended sediment were observed (Figure 4.18d).

In the fifth cruise, patterns of remote sensing reflectance also exhibited distinct characterization of four different optical groups as shown in Figure 4.19 - 4.20. The first group showed large absorption in short wavelengths and large reflectance in long wavelengths which coincided with those stations situated in the surrounding areas of river mouths where relatively high CDOM absorption and suspended sediment were observed (Figure 4.20a). The second group showed relatively small absorption in short wavelengths and relatively small reflectance in long wavelengths which coincided with those stations located in the southeast corner of the Upper Gulf where relatively lower chlorophyll a concentration, CDOM absorption and suspended sediment were observed (Figure 4.20b). The third group exhibited moderate absorption in short wavelengths and moderate reflectance in long wavelengths which coincided with those stations along the NE-SW axis which separated the first two areas (Figure 4.20c). The last group exhibited extremely large reflectance in long wavelengths and relatively small absorption in short wavelengths which coincided with those stations in the northeast corner of the Upper Gulf where relatively higher suspended sediment was observed (Figure 4.20d).

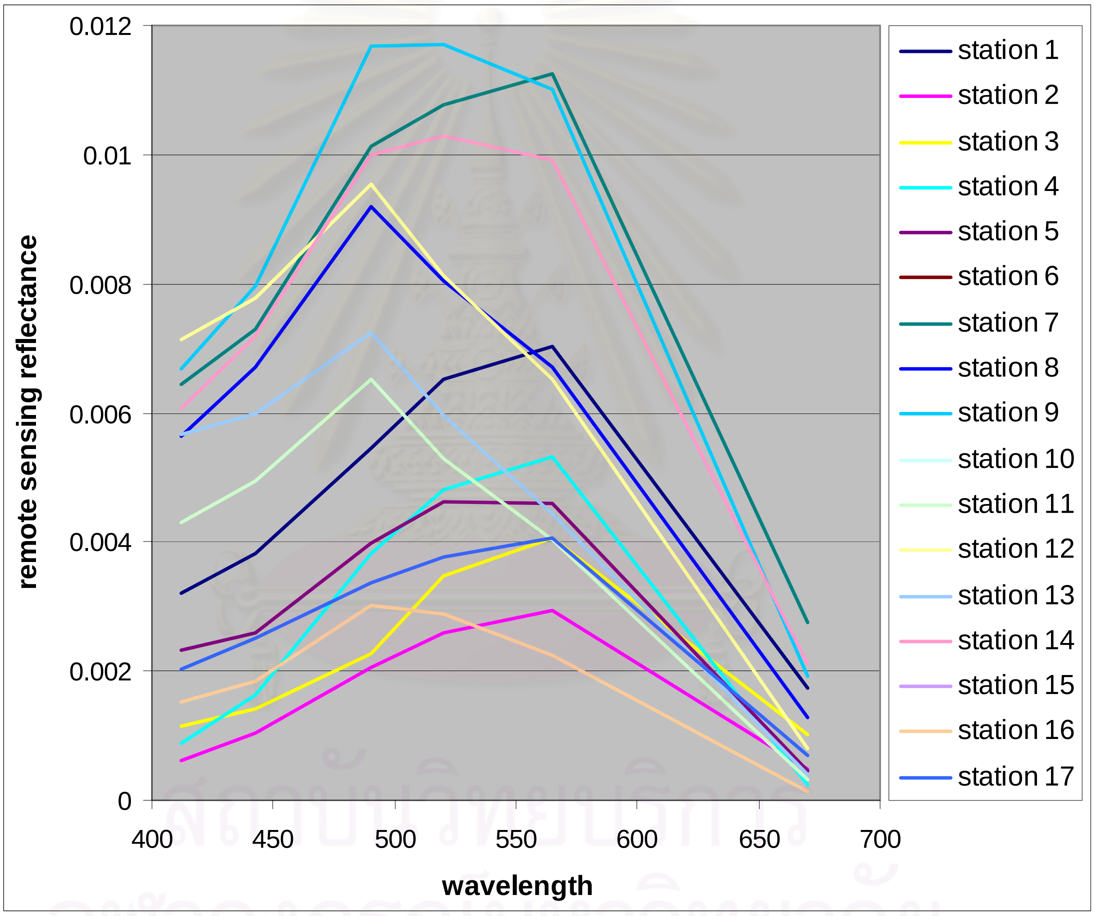

Figure 4.17 Remote sensing reflectance for all stations in cruise 4

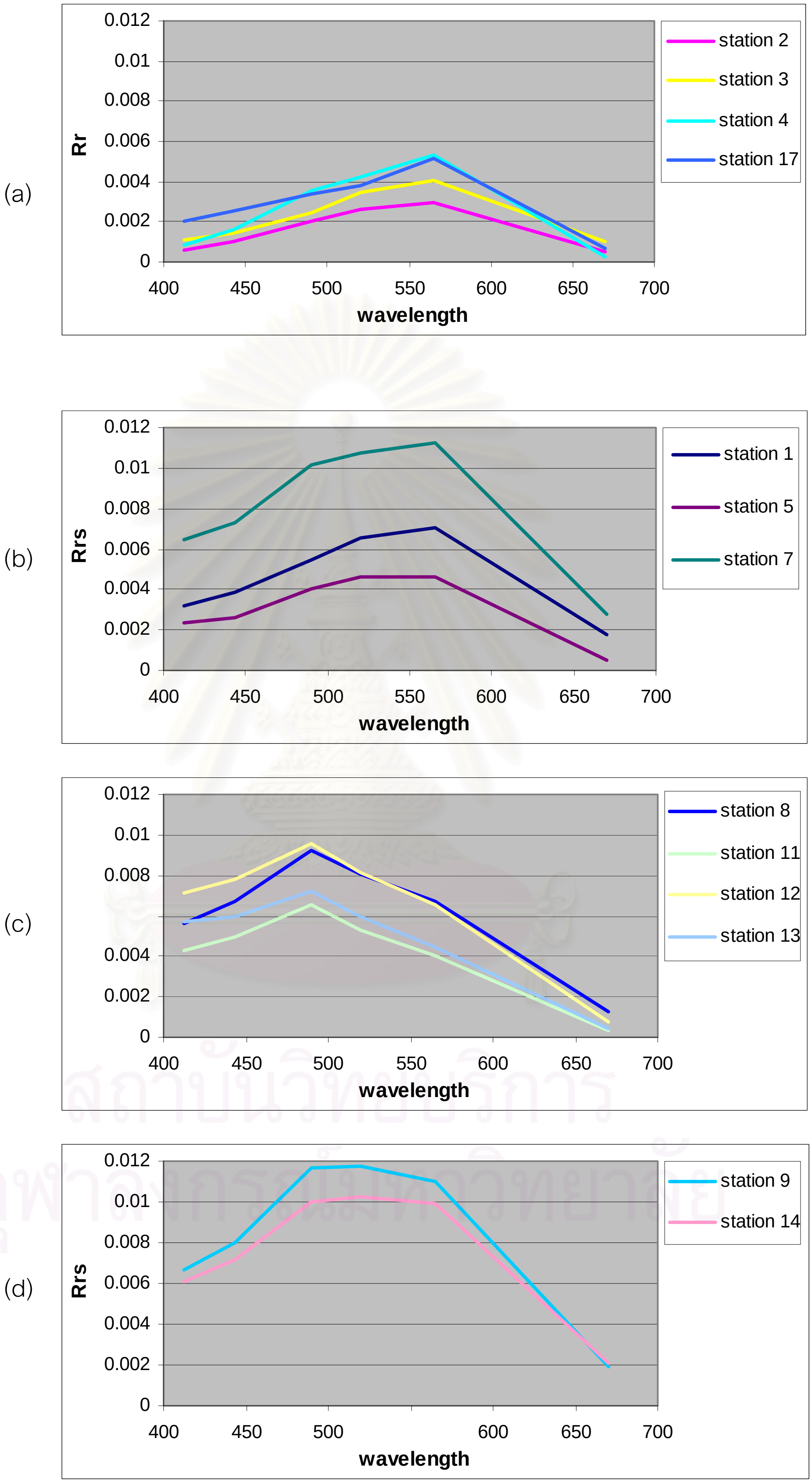

Figure 4.18 Patterns of remote sensing reflectance for cruise 4

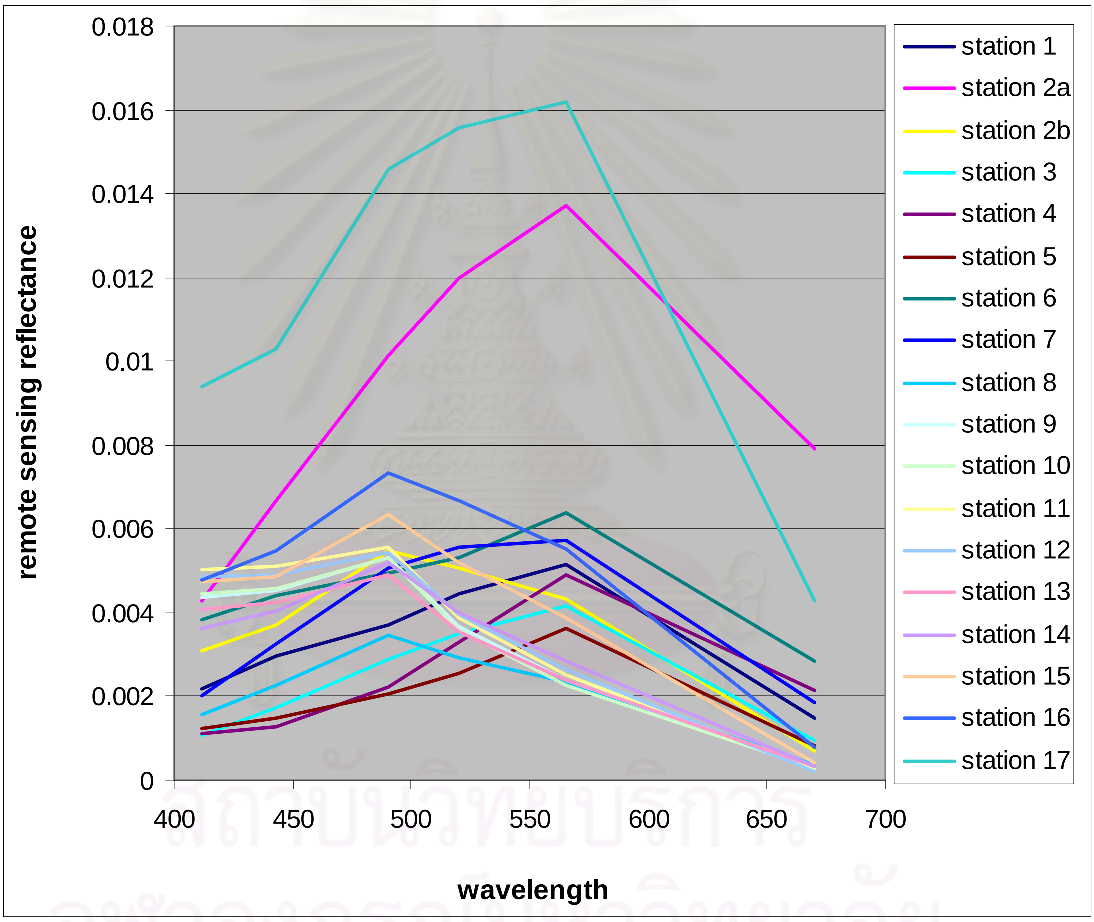

Figure 4.19 Remote sensing reflectance for all stations in cruise 5

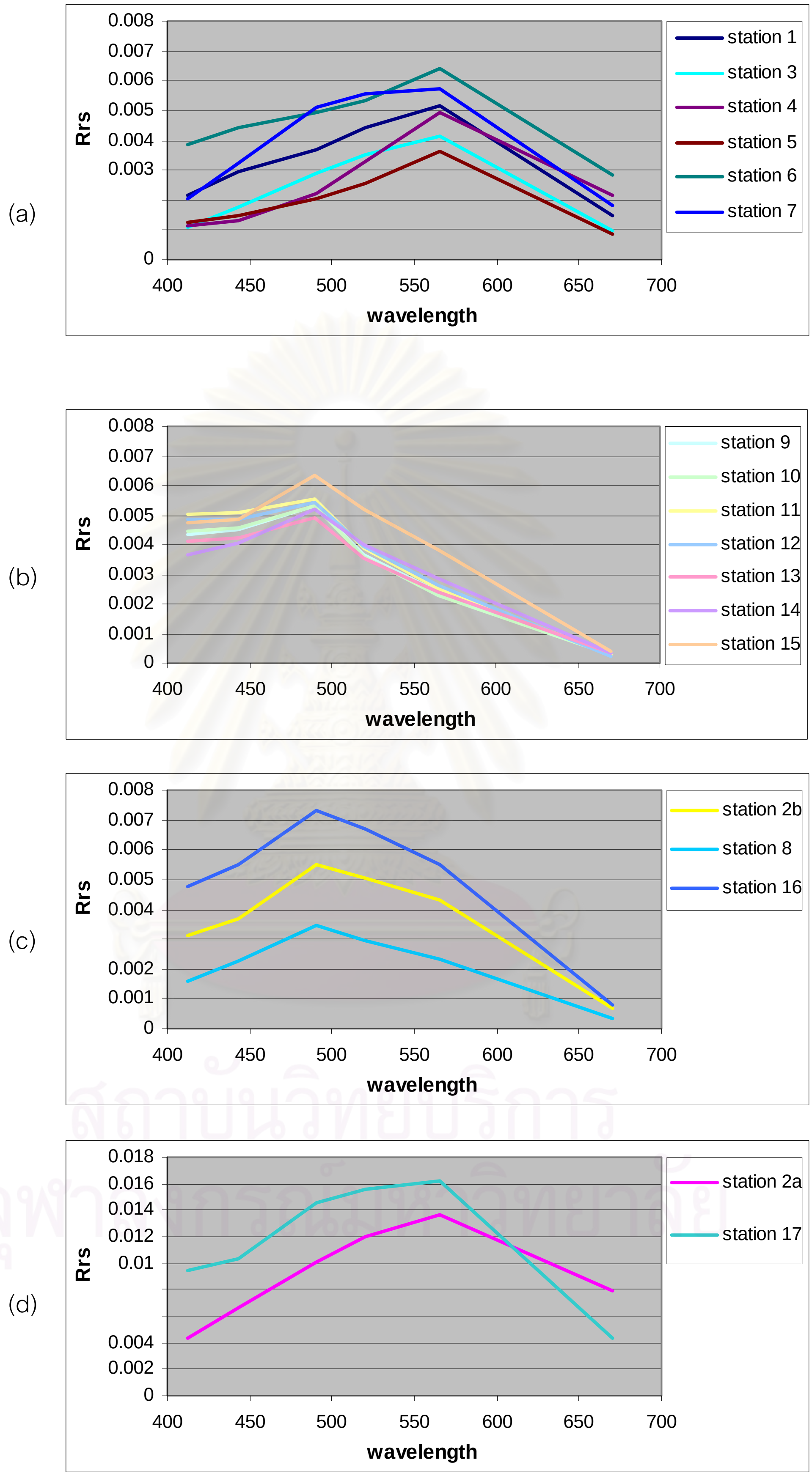

Figure 4.20 Patterns of remote sensing reflectance for cruise 5

4.3 Algorithms development

4.3.1 Algorithm Comparison

In order to compare the sea truth data with the GLI in-water algorithms, spline interpolation technique was used to estimate the remote sensing reflectance (Rrs) at reference wavelengths coincident with the wavebands of GLI in-water algorithms. Consequently, Rrs was converted to the normalized water leaving radiances (NWLR) for validation purposes. GLI in-water algorithms were illustrated by the following mathematical procedures:

$$\begin{aligned} &CHLA = 10\wedge(a_0 + a_1R + a_2R^2 + a_3R^3) + a_4 \\ &a = [0.531, -3.559, 4.488, -2.169, -0.23] \\ &R = \log_{10}(NWLR443 > NWLR460 > NWLR520)/NWLR545) \end{aligned} \tag{2.3}$$

$$\begin{aligned} &CDOM\,440 = 10\wedge(a_0 + a_1R) \\ &a = [-1.493, -1.618] \\ &R = \log_{10}(NWLR443/NWLR520) \end{aligned} \tag{2.4}$$

$$\begin{aligned} &SS = 10\wedge(a_0 + a_1R + a_2R^2) \\ &a = [-0.3186, -1.5935, 0.4376] \\ &R = \log_{10}(NWLR443/NWLR545) \end{aligned} \tag{2.5}$$

$$\begin{aligned} &Kd\,490 = 10\wedge(a_0 + a_1R + a_2R^2 + a_3R^3) \\ &a = [-0.825, -1.362, 1.094, -0.777] \\ &R = \log_{10}(NWLR460/NWLR545) \end{aligned} \tag{2.6}$$

In comparison, the observed and modelled data sets were plotted. Figure 4.21 - 4.24 showed the correlations between the observed and modeled data of chlorophyll, total suspended sediment, coloured dissolved organic matter, and Kd 490, respectively. It is obvious that the graphs illustrated their own weak linear relationships. Accordingly, GLI in-water algorithms exhibited underestimations of the concentrations of three optically active constituents in the Upper Gulf of Thailand. It is suggested that tuning constants of old algorithms was not good solution in algorithm parameterization. Therefore, algorithm developments do need more consideration in empirical approach.

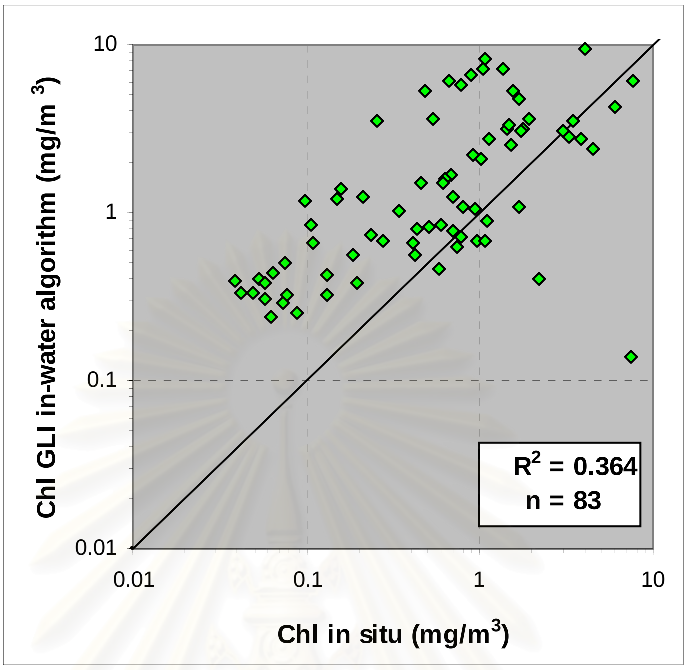

Figure 4.21 Comparison of Chlorophyll observed data and GLI in-water algorithm

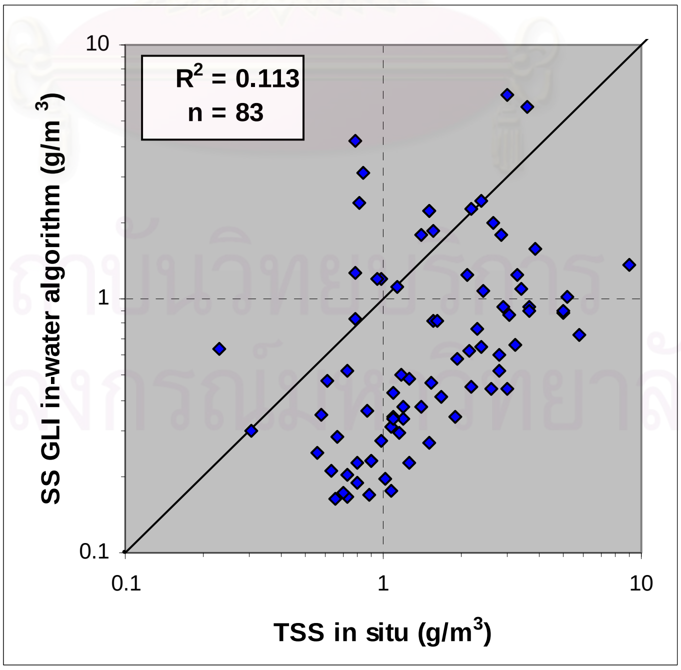

Figure 4.22 Comparison of TSS observed data and GLI in-water algorithm

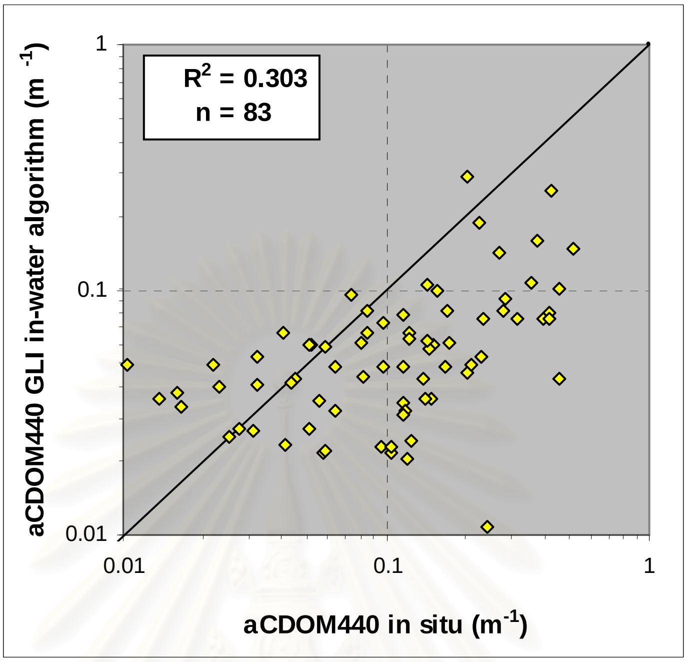

Figure 4.23 Comparison of CDOM observed data and GLI in-water algorithm

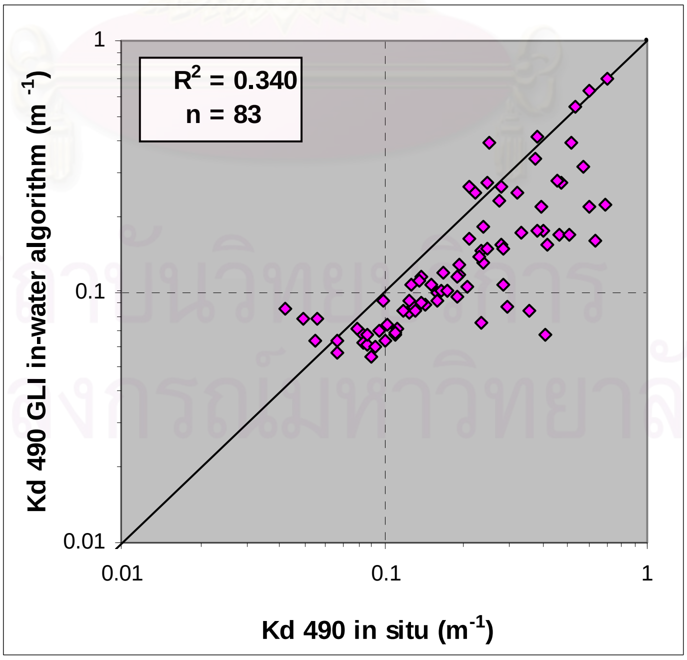

Figure 4.24 Comparison of Kd490 observed data and GLI in-water algorithm

4.3.2 Algorithm design

In order to develop in-water algorithms for each optically active constituent, regression technique was used. Data from the first, the second and the third cruises were constructed in algorithm design whilst data from the other two cruises were left for validation purpose. Nevertheless, the remote sensing reflectance was used instead of normalized water-leaving radiance (nLw) because the atmospheric correction algorithm has not been successfully developed in this area.

4.3.2.1 Chlorophyll-a algorithm

Relationship in a non-linear form of power function between chlorophyll-a concentration and the ratio of the remote sensing reflectance at wavelength 520 nm to 565 nm gave the best suitable curve (Figure 4.25). As a result, band ratio and non-linear regression were applied to determine the new chlorophyll-a algorithm constructed by data set in the first three cruises as illustrated in Figure 4.26. Hence, mathematical procedure in the new algorithm for chlorophyll-a is defined as:

$$\text{Chlorophyll-a (mg/m}^3\text{)} = 1.1828(\text{Rrs520/Rrs565})^{-4.8367} \quad (4.1)$$

$$(R^2 = 0.74, \; n = 51)$$

4.3.2.2 Total suspended sediment algorithm

Relationship in a non-linear form of power function between total suspended sediment concentration and the remote sensing reflectance at wavelength 670 nm gave the best suitable curve (Figure 4.27). Accordingly, non-linear regression of single band was applied to determine the new total suspended sediment algorithm constructed by data set in the first three cruises as illustrated in Figure 4.26. Therefore, mathematical procedure in the new algorithm for total suspended sediment is defined as:

$$\text{Total suspended sediment (g/m}^3\text{)} = 99.355(\text{Rrs670})^{0.5746} \quad (4.2)$$

$$(R^2 = 0.76, \; n = 51)$$

4.3.2.3 Coloured dissolved organic matter algorithm

Relationship in a non-linear form of second order polynomial function between CDOM absorption coefficient at wavelength 412 nm and the ratio of the remote sensing reflectance at wavelength 412 nm to 565 nm gave the best suitable curve (Figure 4.29). As a result, band ratio and non-linear regression was used to determine the new CDOM absorption algorithm constructing by data set in the first three cruises as illustrated in Figure 4.30. Therefore, mathematical procedure in the new CDOM absorption algorithm is defined as:

$$\text{CDOM } (m^{-1}) = 0.362(Rrs412/Rrs565)^2 - 0.929(Rrs412/Rrs565) + 0.586 \quad (4.3)$$

$$(R^2 = 0.71, n = 51)$$

4.3.2.4 Kd-490 algorithm

Relationship in a non-linear form of power function between diffuse attenuation coefficient for downwelling irradiance at wavelength 490 nm and the ratio of the remote sensing reflectance at wavelength 490 nm to 565 nm gave the best suitable curve (Figure 4.31). Accordingly, band ratio and non-linear regression were used to determine the new Kd-490 algorithm constructed by data set in the first three cruises as illustrated in Figure 4.32. Hence, mathematical procedure in the new Kd 490 algorithm is defined as:

$$\text{Kd } 490 \ (m^{-1}) = 0.2411(Rrs490/Rrs565)^{-1.2753} \quad (4.4)$$

$$(R^2 = 0.78, n = 51)$$

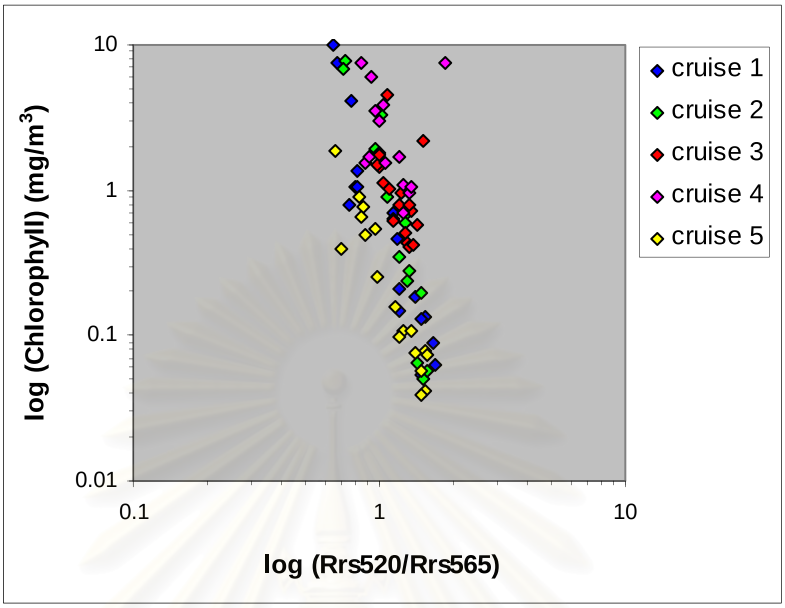

Figure 4.25 Relationship between chlorophyll concentration and Rrs520/Rrs565

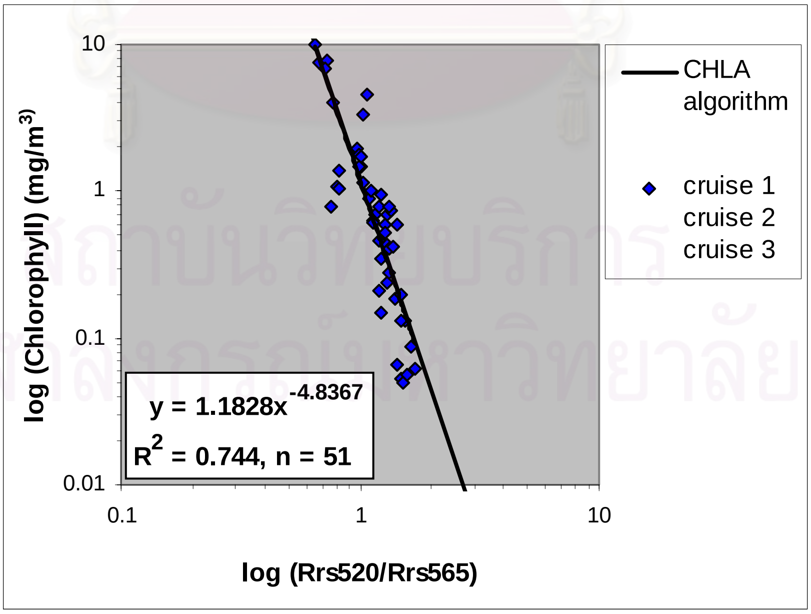

Figure 4.26 New chlorophyll algorithm

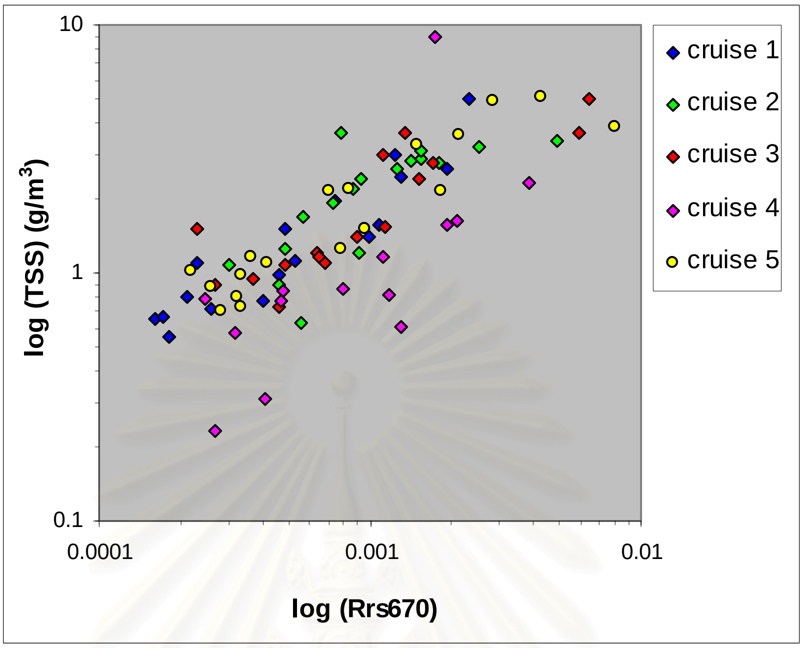

Figure 4.27 Relationship between total suspended sediment concentration and Rrs670

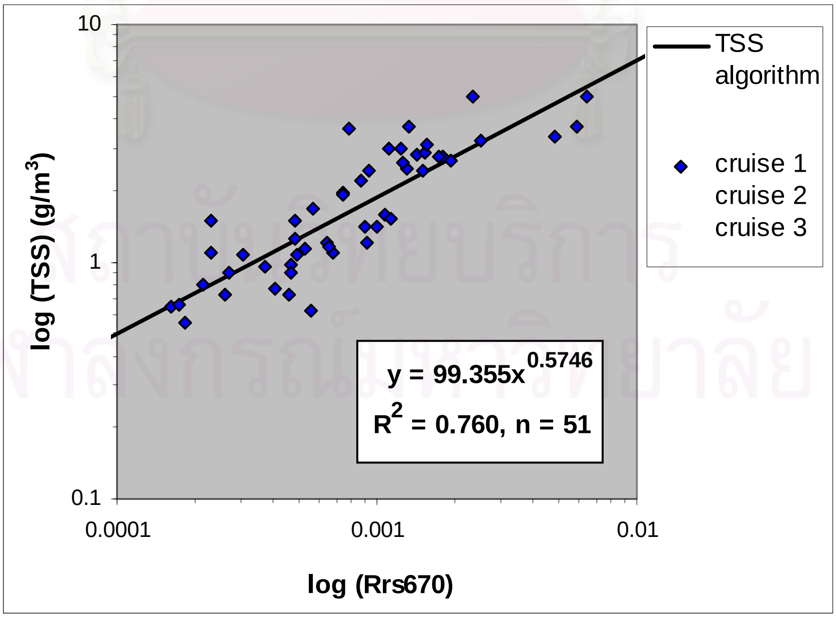

Figure 4.28 New total suspended sediment algorithm

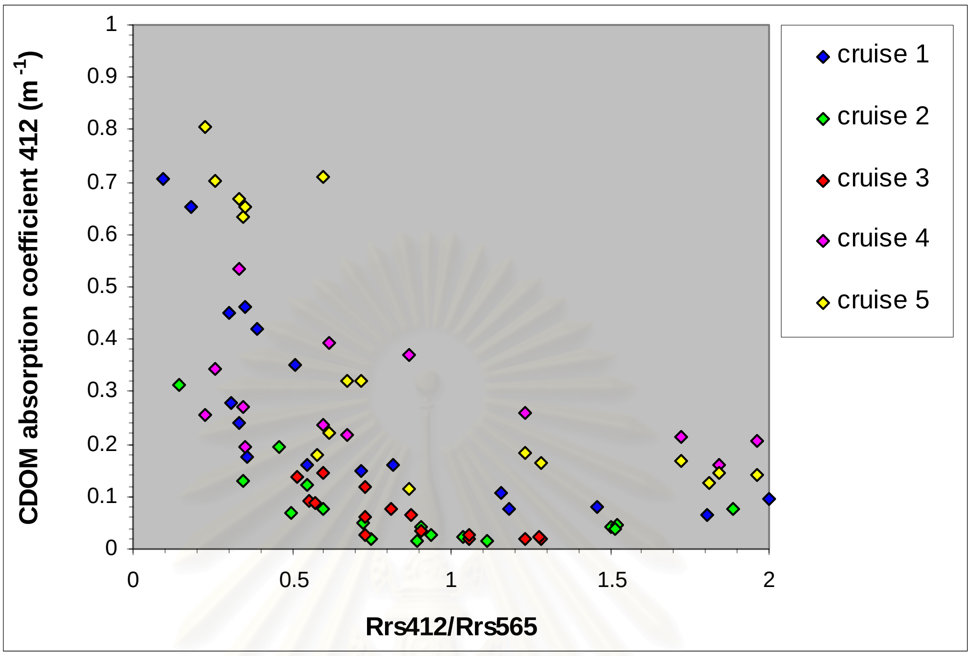

Figure 4.29 Relationship between CDOM absorption at 412 nm and Rrs412/Rrs565

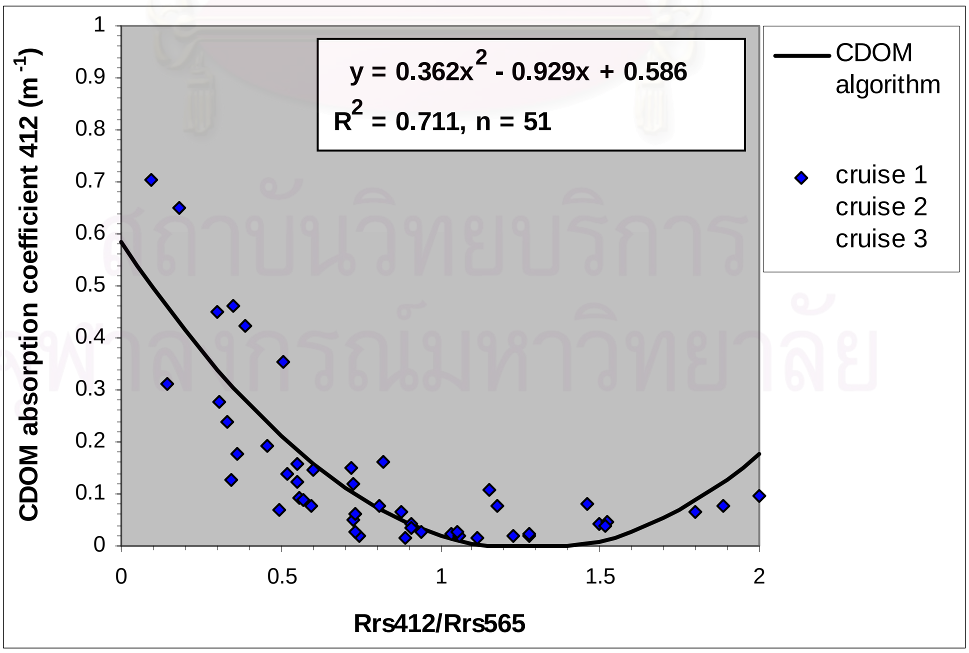

Figure 4.30 New CDOM absorption algorithm

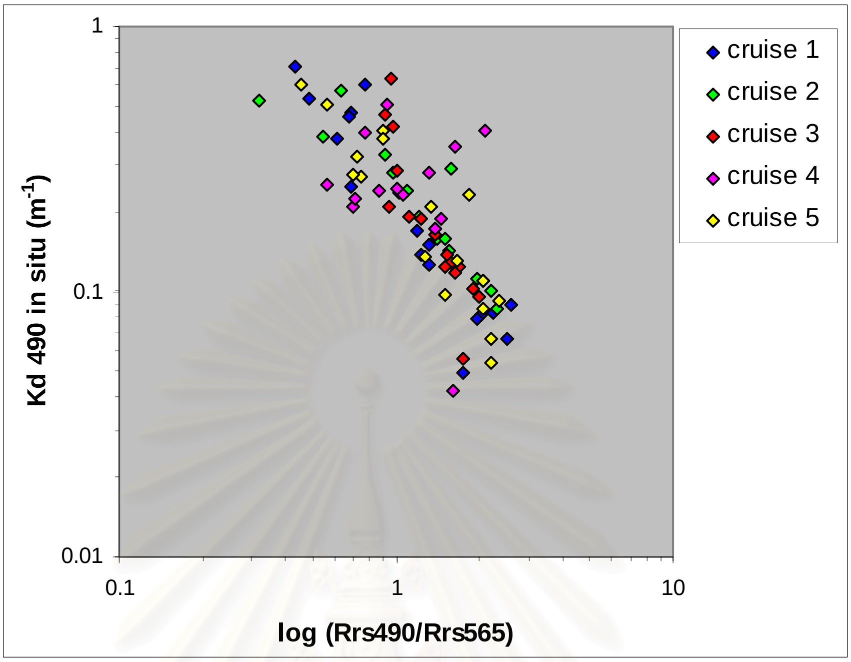

Figure 4.31 Relationship between Kd 490 and Rrs490/Rrs565

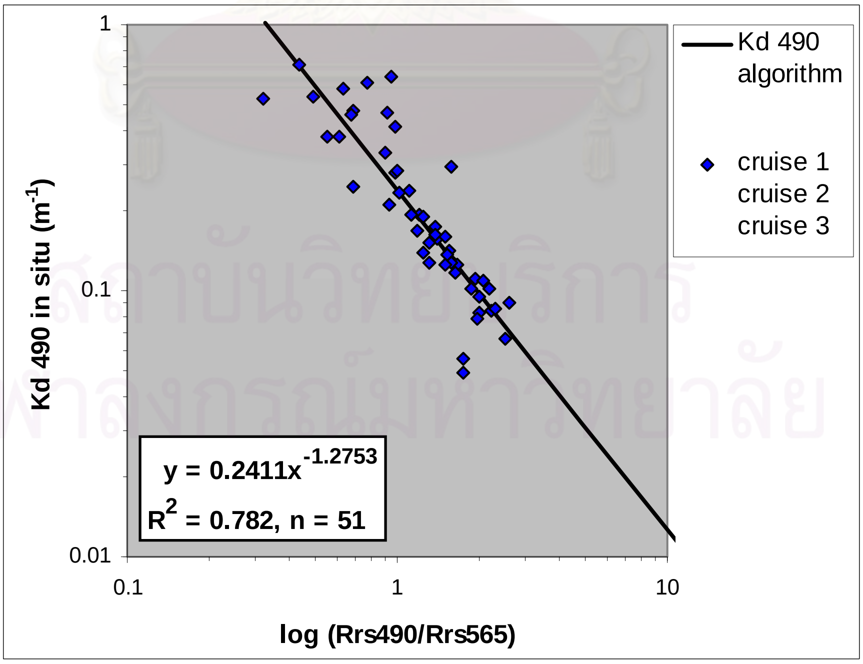

Figure 4.32 New Kd 490 algorithm

4.3.3 Algorithm validation

In order to examine the applications of these new in-water algorithms and their accuracies, the data set from the fifth cruise were applied for validation purpose. It was noted that the data set from the forth cruise observation were reasonably ignored in taking into consideration due to unsuitable weather condition during ship deployment. Since measurement of underwater light field by the profiling reflectance radiometer needs by nature appropriately clear sunlight condition, such weather conditions as cloud coverage and rain hampered the sea truth survey to estimate the bio-optical data. Accordingly, the data set from the forth cruise were not included in validation process as mentioned above.

Validations of the new in-water algorithms gave good results as illustrated in Figure 4.33 – 4.36. The black line showed the equation of new algorithms which were constructed by the data set from the first three cruises. The yellow dots were the data set from the fifth cruise applying in validation. There were totally 18 station data and all of them were totally used in validation purpose. Even if once such a spiking data was excluded, it would suddenly give a higher correlation (R^2 rose up to more than 0.9). Nevertheless, it was preferable not to pretend that way because there would be a bias against the validation purpose.

The validations gave satisfactory results with acceptable correlations. Figure 4.33 – 4.36 resulted that R^2 values were 0.73, 0.71, 0.70 and 0.84 for the new chlorophyll, suspended sediment, CDOM absorption and Kd490 algorithms, respectively. Therefore, it is suggested that those new in-water algorithm are applicable of measuring the actual examples in the Upper Gulf of Thailand.

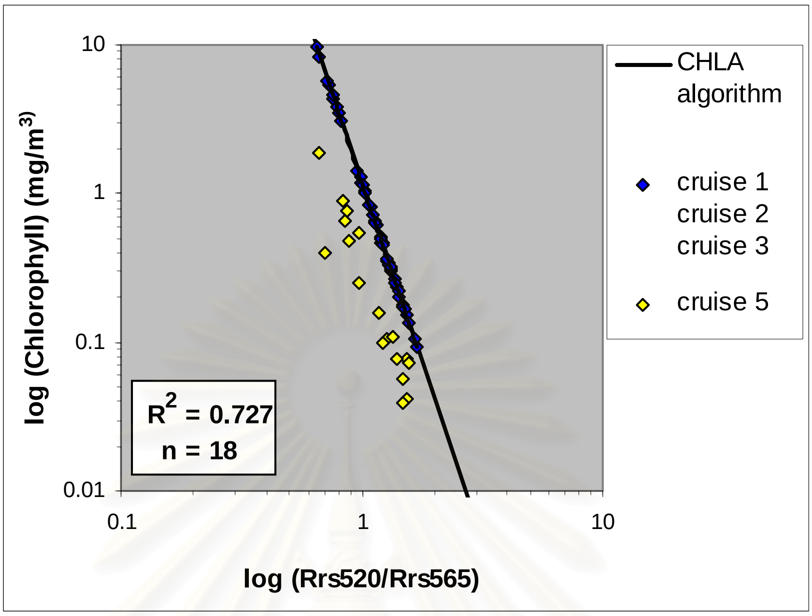

Figure 4.33 Validation of the new chlorophyll algorithm

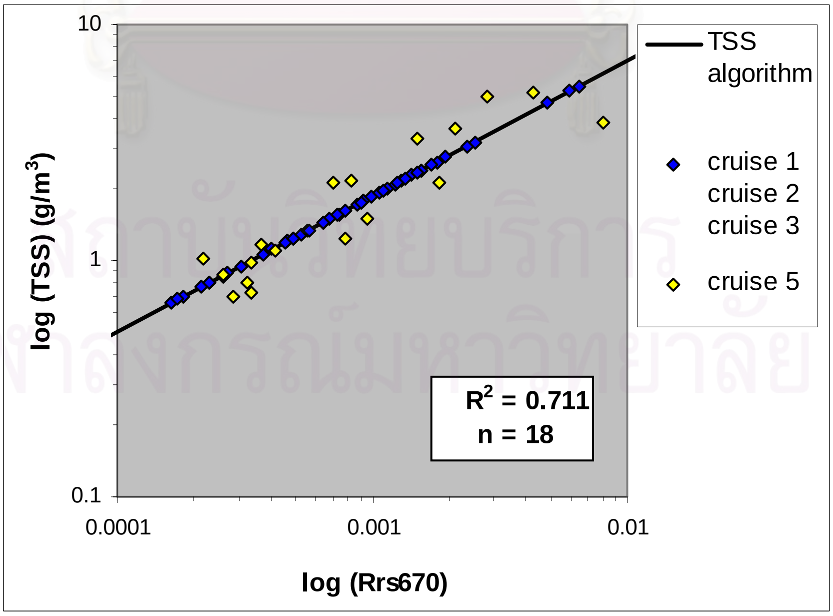

Figure 4.34 Validation of the new total suspended sediment algorithm

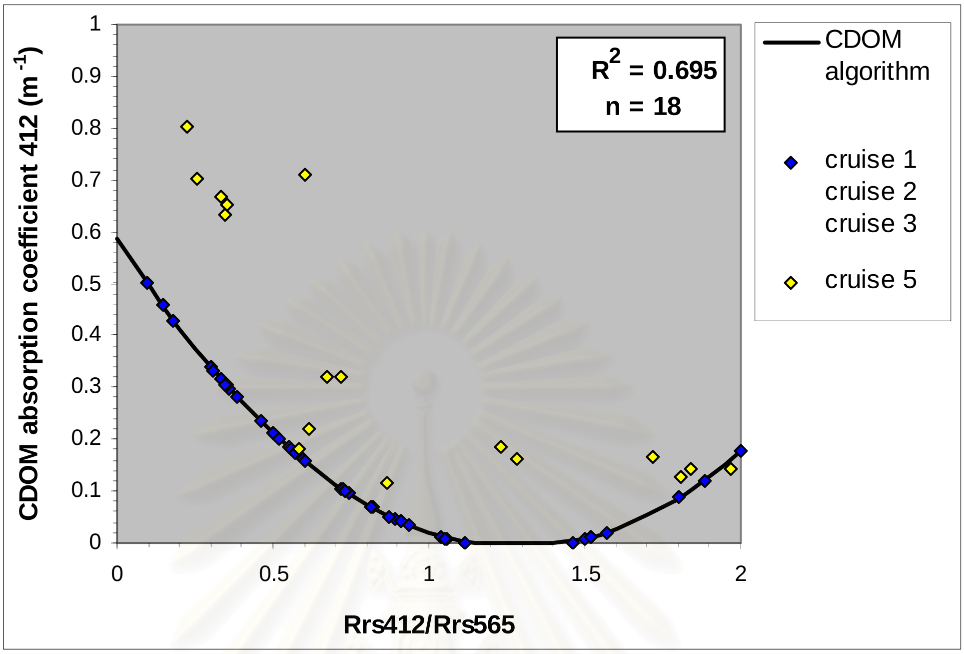

Figure 4.35 Validation of the new CDOM absorption algorithm

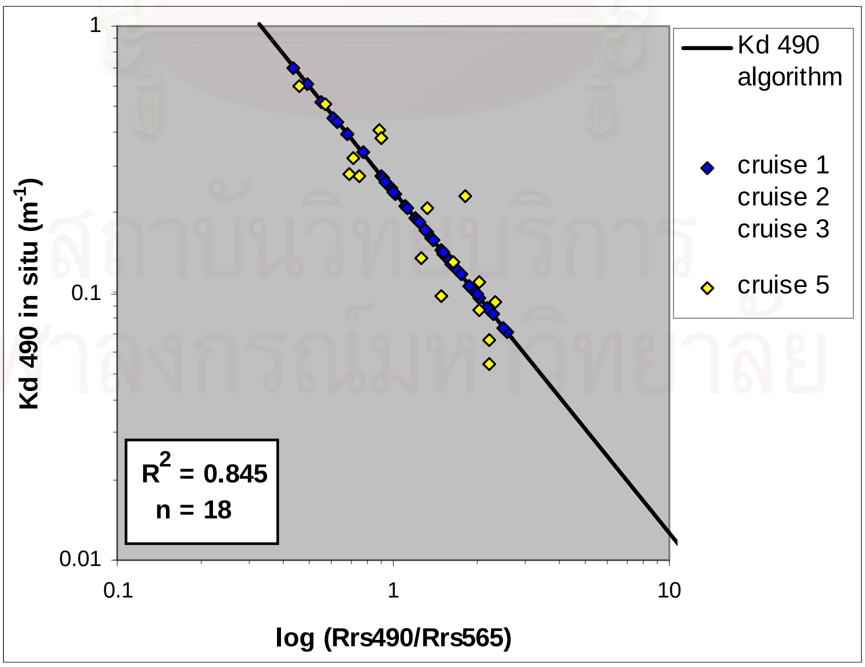

Figure 4.36 Validation of the new Kd 490 algorithm

CHAPTER V

DISCUSSION

5.1 In-water algorithms for the Upper Gulf of Thailand

The improved algorithms were simple empirical relationships based on the remote sensing reflectance and measurements of the products of interest present. There were no physical assumptions and the equations were derived from the best fits of their relation curves. Accordingly, the advantages of empirically derived algorithms are that they are simple, easy to derive even from a limited number of measurements, and easy to implement and test. In general, they yield stable results and have a short computing time due to their mathematical simplicity. By their nature, empirical algorithms for coastal waters are always regional in scope. As a result, such concentrations are not frequently observed in most areas of the Upper Gulf of Thailand, therefore the algorithm might be applicable under the majority of conditions particularly consideration for the amount of terrestrial discharges from the four main rives. In addition, it is strongly suggested that applications of those new algorithms are incapable of applying in such unsuitable weather conditions as cloudy and rainy skies.

The algorithms therefore appear to be working satisfactorily for this region. Figure 5.1 - 5.4 showed the accuracies of these new algorithms with acceptable results. Results showed correlations with R-square 0.64, 0.72, 0.64 and 0.86 for chlorophyll-a, total suspended sediment, CDOM absorption and Kd490 algorithms, respectively. However, it was assumed the water to be homogenous without stratification effects. Most of all, it should be noted that the empirical approach provides relationships which possibly explain the state of system at only such a specific time due to the fact that coastal water does not always perform the same typical optical characteristics. Therefore, it should be considered carefully in using applications of these algorithms.

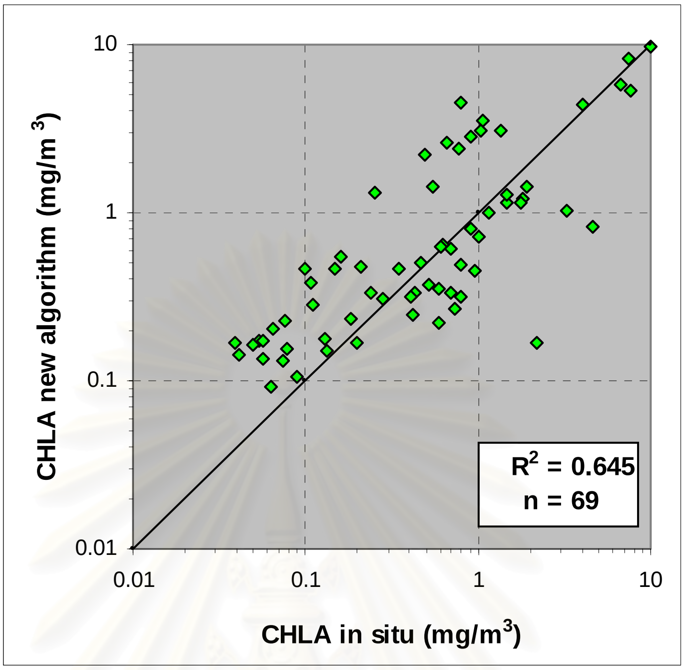

Figure 5.1 Accuracy of the new chlorophyll-a algorithm

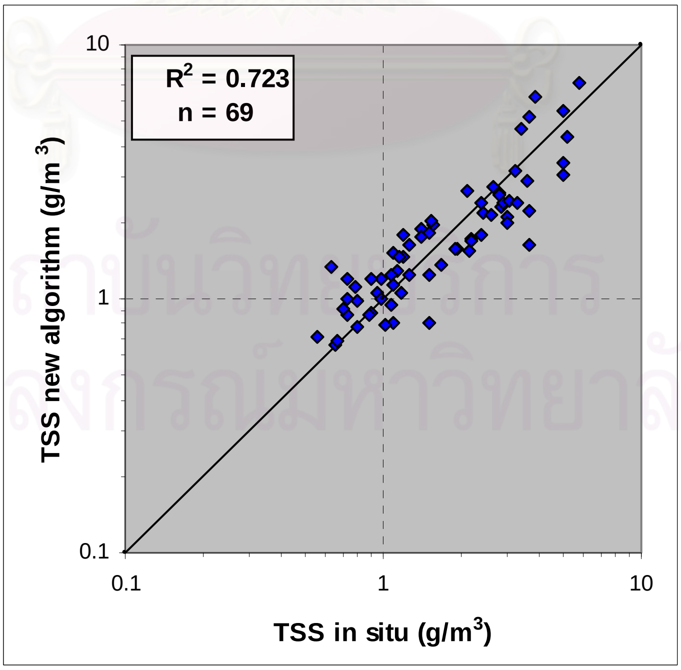

Figure 5.2 Accuracy of the new total suspended sediment algorithm

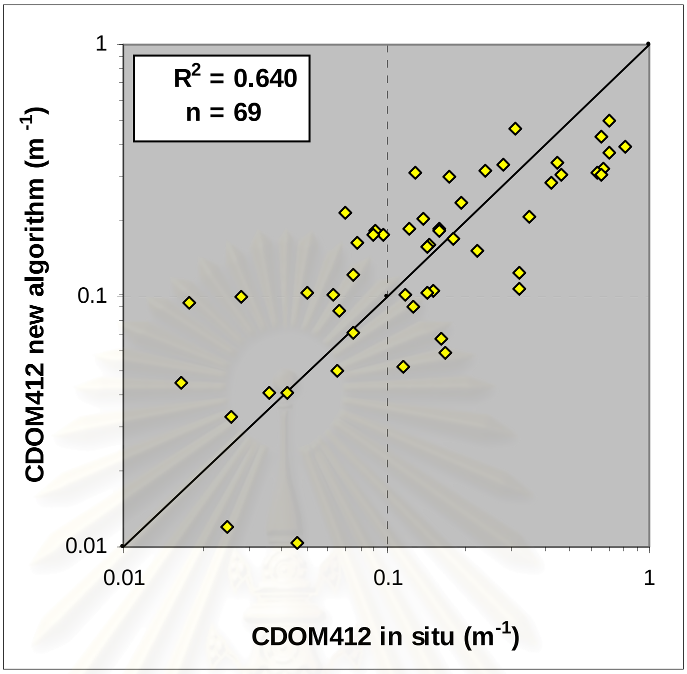

Figure 5.3 Accuracy of the new CDOM absorption algorithm

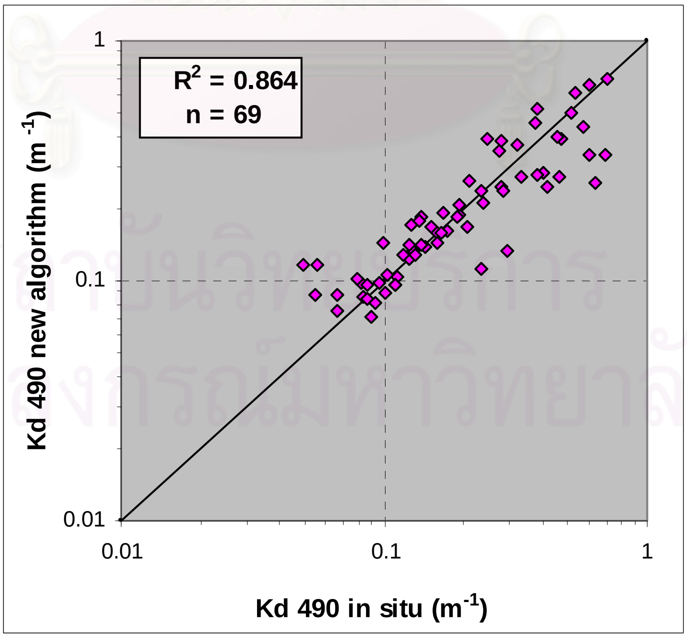

Figure 5.4 Accuracy of the new Kd 490 algorithm

5.1.1 Chlorophyll algorithm

The absorption in the live population of phytoplankton is affected by the packaging effect of the pigments within the cells. This tends to broaden the absorption peaks of the natural population compared with what is observed in isolated extracted pigment samples in laboratory. The water surrounding the phytoplankton will also contain dissolved organic compounds derived as waste from the primary production and decaying dead cells. These contain other pigments such as phaeophytin-a, each with its individual absorption spectrum. While the pigments on their own do not scatter the light, the population of phytoplankton cells has a physical structure which is optically equivalent to particulate material, acting to scatter light.

Even though the new chlorophyll algorithm was improved in term of power function, the best fit correlation shows changes by seasonal variation. As a result, it was found the relationships between chlorophyll concentration and Rrs520/Rrs565 varied with seasonal condition according to southwest and northeast monsoons as illustrated in Figure 5.1. Therefore, it is suggested that the coefficients of the algorithms be switched smoothly between these two monsoon seasons over the area.

In addition, there was a correlation between chlorophyll-a concentration and total suspended sediment using the remote sensing reflectance at 443 nm (Figure 5.2). This relationship can be divided into two optical conditions: Rrs443 is less than 0.004 and Rrs443 is more than 0.004. Apparently, this is suggested that organic fraction of total suspended sediment exhibits a similar absorption characteristic pattern to that of phytoplankton pigments. Furthermore, it would possibly to design another new algorithm to calculate the total suspended sediment as a function of chlorophyll-a concentration.

(a) (b)

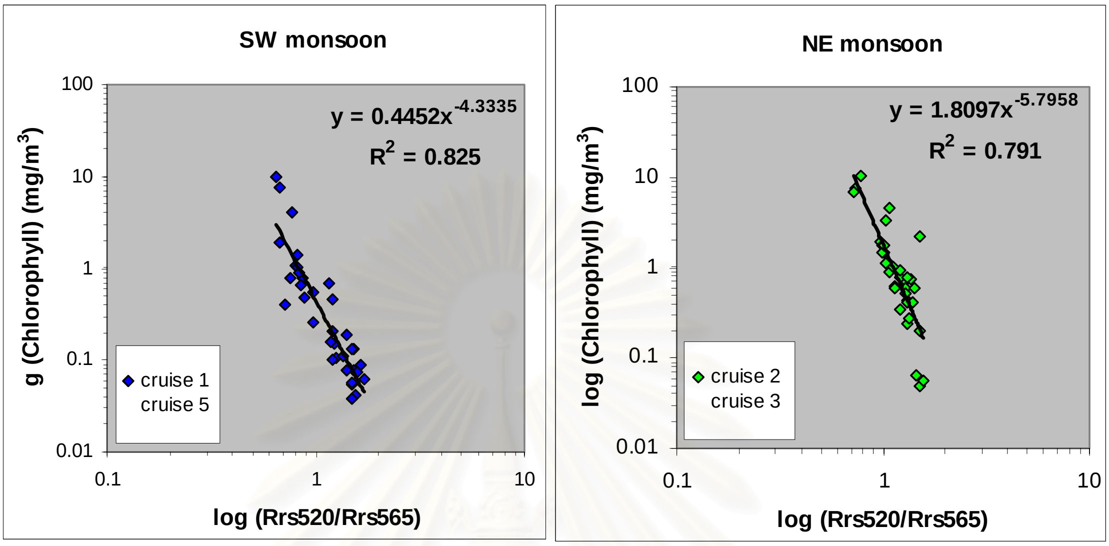

Figure 5.5 Relationships between chlorophyll and Rrs520/Rrs560 with seasonal variation: (a) southwest monsoon and (b) northeast monsoon

(a) (b)

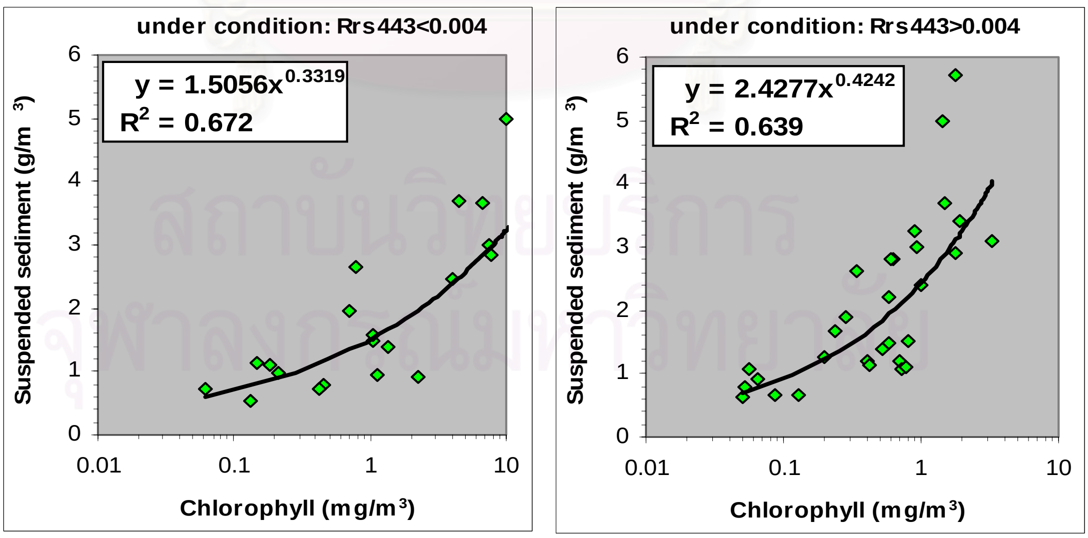

Figure 5.6 Relationship between chlorophyll and total suspended sediment (a) under condition Rrs443 < 0.004, and (b) under condition Rrs443 > 0.004

5.1.2 Total suspended sediment algorithm

Remote sensing reflectance at 670 nm is the most successful method of obtaining total suspended sediment concentrations regardless of seasonal variability and its composition. The success of this algorithm will enable the continuing study of suspended sediment distribution in the Upper Gulf of Thailand over spatial scales not previously possible.

With regard to sediment composition, the relationship between total suspended sediment and Rrs443/Rrs565 exhibited two distinct populations (Figure 5.3). Obviously, total suspended sediment exhibited two kinds of optical characteristics. One is the spectrum absorption body like as phytoplankton and the another one is scattering body like as clay mineral. In other words, total suspended sediment includes both organic and inorganic fractions as shown in Appendix E. Organic fraction is mainly produced among the estuarine environment by various physicochemical processes as mentioned previously. On the other hand, inorganic fraction is supplied from riverine particulate materials.

In addition, measurement of total suspended sediment concentration might include considerable error from the atmospherically transported particles which is known as foreign dusts. Therefore, it would be valuable to be able to obtain further information on the nature of suspended sediment, for instance, successfully deriving the contributions of both organic and inorganic proportions to total suspended sediment.

5.1.3 CDOM absorption algorithm

The quantitative analysis of CDOM is shown as an absorption coefficient. CDOM absorption coefficient increases exponentially with decreasing wavelength. Absorption coefficient at 412 nm can be used as an index of CDOM concentration. However, in case of using CDOM as a correction factor for chlorophyll concentration, it is suggested that it be wavelength near 443 nm where the maximum absorption by chlorophyll-a occurs. The new CDOM absorption algorithm might seem to be inaccurate because river inflows can vary greatly in case of raining during the ship deployment.

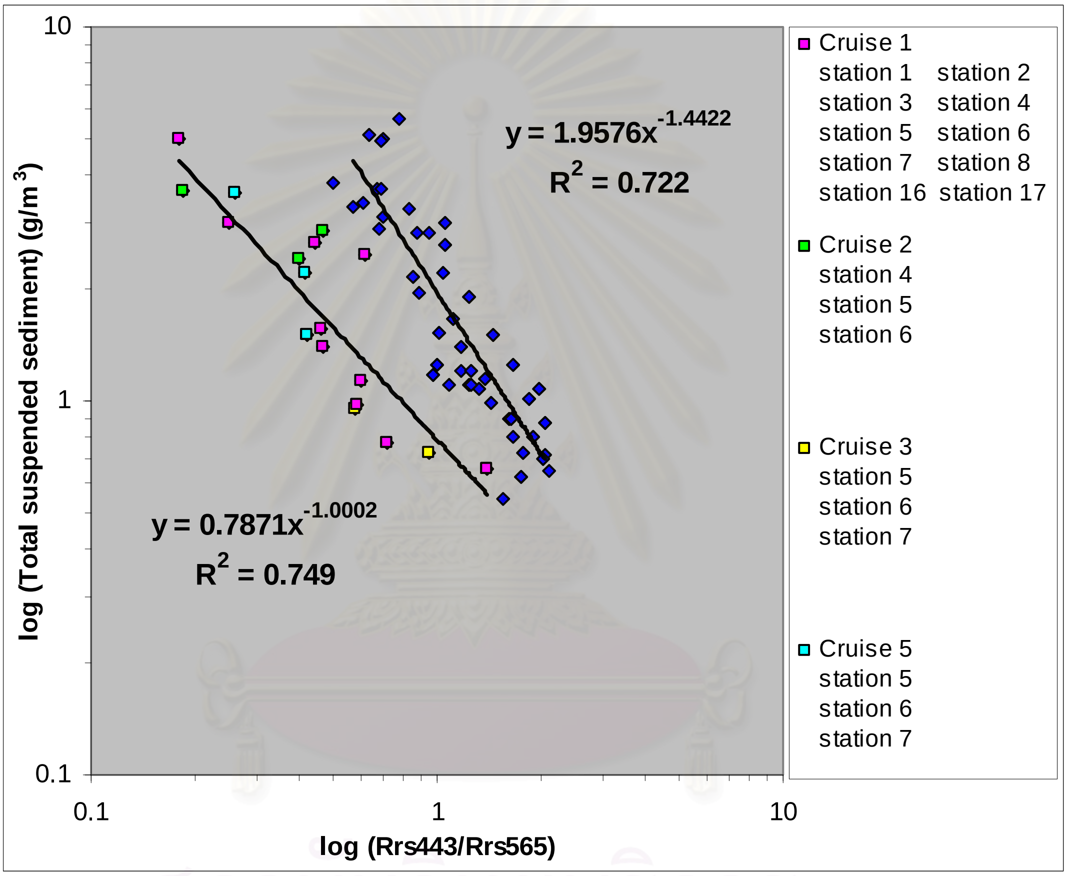

Figure 5.7 Relationship between total suspended sediment and Rrs443/Rrs565

It can separate two optical types of organic and inorganic suspended sediments.

5.2 Optical variability of the Upper Gulf of Thailand

Coastal waters are by nature highly dynamic environments that experience a variety of processes which alter their optical properties. As mentioned previously, the optical properties of the Upper Gulf of Thailand are much complex due to the variable proportions of materials from terrestrial discharges of four main rivers as stated. Therefore, all optically active constituents can vary independently in the coastal zone as a result of terrestrial discharges and bottom resuspension. As a result, higher concentrations of chlorophyll, total suspended sediment and dissolved organic matter were associated with those river inflows.

In relation to freshwater inflow, it is apparently suggested that there are catchment-related patterns in the fluvial transports containing dissolved and particulate, organic and inorganic materials transported into the Upper Gulf of Thailand. Human activities in catchment areas (e.g. agricultures, municipalities, and industries) can all result in major changes in the volume and pattern of riverine runoff and in increased loads of nutrients and suspended sediments into coastal waters particularly in the vicinity of river mouths. Changes in patterns of freshwater runoff due to catchment modification may profoundly affect circulation and salinity regimes in estuaries and adjacent coastal regions, with impacts on key habitats (e.g. mangroves, communities).

Regarding river input, when transported into the estuary which acts as filters, those materials are influenced by factors from varying physicochemical constraints. These physicochemical parameters, including pH, redox potential, salinity, nutrients and the concentrations of complexing ligands, undergo major variations in estuary. Accordingly, dissolved-particulate transformations are driven by estuarine stress status, for example, flocculation-aggregation, precipitation, absorption-desorption at surfaces of suspended sediment and uptake via biological processes. Obviously, the exchange processes between the three fractions (dissolved, colloidal and particulate) are more complex than sometimes supposed and the disappearance of colloids can enrich particulate matter or return back to dissolved phase.

The Upper Gulf of Thailand is definitely considered as a very complex estuarine environment in which the boundary conditions are extremely variable in both space and time. For ocean colour remote sensing application of coastal shallow waters, it is obviously important to understand the effects that some of these processes have on the optical characteristics of the bottom boundary layer. Waves and tides, for example, resuspend sediments in varying degrees depending on bottom topography, sediment composition and characteristics and the strength of the forcing mechanism. Accordingly, the river mouths along the north and northwest corners are shallow areas where tidal current can stir and resuspend bottom sediment whilst the southeast corner is so deeper that resuspension of bottom sediment is less.

In addition to marine environment, there is a shift in the species and pigment composition and in the characteristic optical properties of phytoplankton with a change in chlorophyll-a concentration. Differences in pigment composition across algal classes are well-known, and methods exist to convert HPLC pigment composition, for example, to algal composition. These differences in pigment composition can also translate into differences in shape of pigment absorption spectra, although some pigment changes (e.g. in composition of carotenoids) may have only minimal effects on absorption peaks. However, there may also be differences among algal groups in back-scattering spectra. It is not so clear to what extent the inverse problem is tractable to distinguish pigment composition or algal class based on differences in remote sensing reflectance (Rrs). There are certainly some algal classes and pigment groups, such as cyanobacterium *Trichodesmium sp.* and coccolithophorid species that are readily distinguished, at least at elevated bloom densities. There may also be signatures in photo-protective pigments in the UV that can be used to distinguish taxa (IOCCG, 2000).

In the long run, species composition is of great importance in biological and ecological studies and there is certainly some interest in developing the potential of remote sensing to distinguish various types of phytoplankton. However, this task is likely to be even more difficult in coastal waters like the Upper Gulf of Thailand.

With regard to CDOM, its concentration has a great variability at low salinity. It is apparent that CDOM be considered to be refractory material that can escape degradation in the fluvial-estuarine environments. In other words, CDOM behaves in a conservative manner. As a result, CDOM can be used as an indicator of riverine input. The magnitude of CDOM absorption was found to vary seasonally depending on the magnitude of the terrestrial discharges and was inversely related to salinity distribution. However, a significant correlation was also observed between CDOM absorption and chlorophyll concentration that the in situ formation of CDOM from phytoplankton was also playing a role. Moreover, there is evidence that CDOM is produced within sediments and that high levels of CDOM absorption and fluorescence exist within sediment porewaters (IOCCG, 2000).

With respect to Kd490, it has wide range of applicability in ocean optics, as it is directly related to the presence of scattering particles in the water column, either organic or inorganic. Furthermore, Kd490 is a valuable tool for continuous monitoring of the optical properties associated with plankton blooms. The extent of eutrophication is usually limited to few tens of kilometers from major river discharge points. Therefore, it is obvious that all marine hot spots in terms of water quality degradation are associated with the vicinity of river mouths.

The optical properties of the Upper Gulf of Thailand vary greatly over time. Water type and its optical characteristics can change dramatically over the distance, Strong coastal features such as plumes and fronts can move rapidly driven by tides currents and variable seasonal winds. Accordingly, it is essential that validation data be taken as close as possible to the exact time and place of the ship deployment. Even a difference could invalidate the comparisons if there is significant natural variation in the local waters. Ideally, regional or seasonal variations with respect to composition of water constituents, inherent optical properties, variability ranges or correlations between parameters and variables have also to be accounted.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

This study suggested the in-water algorithms for the Upper Gulf of Thailand in order to retrieve the concentrations of three optically active constituents which are chlorophyll-a (CHLA), total suspended sediment (TSS), coloured dissolved organic matter (CDOM) as well as the diffuse attenuation coefficient for downwelling irradiance (Kd490). The improved algorithms are as follows:

$$\text{CHLA } (mg/m^3) = 1.1828(Rrs520/Rrs565)^{-4.8367}$$

$$\text{TSS } (g/m^3) = 99.355(Rrs670)^{0.5746}$$

$$\text{CDOM 412 } (m^{-1}) = 0.362(Rrs412/Rrs565)^2 - 0.929(Rrs412/Rrs565) + 0.586$$

$$\text{Kd 490 } (m^{-1}) = 0.2411(Rrs490/Rrs565)^{-1.2753}$$

These algorithms appear to be working satisfactorily for the Upper Gulf of Thailand. However, coastal water does not always perform the same optical characteristics type. The purpose of using these algorithms should be considered carefully all the time and selected the most proper algorithm for that.

The optical variability of the Upper Gulf of Thailand is mainly influenced by freshwater inflows, resuspension of bottom sediment as well as sediment composition and characteristics. In addition, the state of system changes with weather and seasons. However, the optical properties of the Upper Gulf of Thailand are too much complex for understanding all of these interdependencies.

6.2 Recommendations

This study seemed to be an initial investigation on optical oceanographic survey in the Upper Gulf of Thailand. The improved algorithms appear to be working satisfactorily for this region. However, to conduct the more field data is recommendable, it would be able to rectify and validate the algorithms more precisely.

As far as it should be concerned, next further step should be taking into consideration on atmospheric correction for this region since the optical aerosol performs typical characteristics depending on a specific region. After combining the atmospheric correction and in-water algorithms, we can use the satellite ocean colour sensor for mapping these parameters with minimal sea truth observation. Moreover, it would be applied to study the relationship of these parameters among many others with the phenomena such as phytoplankton bloom and sediment transport. Besides, further investigation to derive a more universally applicable algorithm is therefore necessary covering the whole areas of the Gulf of Thailand.

With respect to the optical variability, further research is certainly needed to describe the system more completely. In addition, the optical model should be established consisting of following components: (1) the forward numerical modeling for solving the radiative transfer equation (2) the empirically-based coupled hydrodynamic-optical models for bottom-boundary layer effects, and (3) the semi-analytical models for remote sensing of optically shallow waters that includes the optical effects of the bottom boundary layer and suspended sediments in the water column.

In addition to optical variability studies, the difficulty is that the relationship between ocean colour and constituents of the water may vary regionally or seasonally, according to the composition of algal species, size distribution of phytoplankton cells, mineral composition of the inorganic particles in suspension or chemical composition of dissolved organic substances. Therefore, further studies do need to be investigated.

REFERENCES

Barbini, R., Colao, F., Fantoni, R., Ferrari, G.M., Lai, A., and Palucci, A. 2003. Lidar fluorosensor calibration of the SeaWiFS chlorophyll algorithm in the Ross Sea. <u>International Journal of Remote Sensing</u> 24: 3205-3218.

Binding, C. E., Bower, D. G., and Mitchelson-Jacob, E. G. 2003. An algorithm for the retrieval of suspended sediment concentrations in the Irish Sea from SeaWiFS ocean colour satellite imagery. <u>International Journal of Remote Sensing</u> 24: 3791-3806.

Blough, N.V., and Vecchio, R.D. 2002. Chromophoric DOM in the coastal environment. <u>Biogeochemistry of Marine Dissolved Organic Matter</u>. Hansell, D.A. and Carlson, C.A. (ed.), San Diego: Academic Press, pp.509-546.

Bricaud, A., Morel, A. and Prieur, L. 1981. Absorption by dissolved organic matter of the sea (yellow substance) in the UV and visible domains. <u>American Society of Limnology and Oceanography</u> 26: 43-53.

Bukata, R.P., Jerome, J.H., Kondratyev, K.Y., and Pozdnyakov, D.V. 1995. <u>Optical Properties and Remote Sensing of Inland and Coastal Waters</u>. CRC Press, 362pp.

Bulgarelli, B. and Zibordi, G. 2003. Remote sensing of ocean Colour: accuracy assessment of an approximate atmospheric correction method. <u>International Journal of Remote Sensing</u> 24: 491-509.

Campbell, J. 1999. <u>Ocean Color Algorithms: Case 1 Waters and Case 2 Waters</u>. University of New Hampshire, 14pp.

Carder, K.L., Chen, R.F., Lee, Z.P., Hawes, S.K., and Kamykowski, D. 1999. Semianalytic moderate-resolution imaging spectrometer algorithms for chlorophyll-a and absorption with Bio-optical domains based on nitrate depletion temperatures. <u>Journal of Geophysical Research</u> 104: 5403-5421.

DeGrandpre, M.D., Vodacek, A., Nelson, R.K., Bruce, E.J., and Blough, N.V. 1996. Seasonal seawater optical properties of the U.S. Middle Atlantic Bight. Journal of Geophysical Research 101: 722-736.

Gordon, H.R. 1994. Modeling and Simulating Radiative Transfer in the Ocean. Ocean Optics. Spinrad, R.W., Carder, K.L., Perry, M.J. (ed.), Oxford Monographs on Geology and Geophysics No.25, Oxford University Press, pp.3-39.

Hu, C., Muller-Karger, F.E., Biggs, D.C., Carder, K.L., Nababan, B., Nadeau, D., and Vanderbloemen, J. 2003. Comparison of ship and satellite bio-optical measurements on the continental margin of the NE Gulf of Mexico. International Journal of Remote Sensing 24: 2597-2612.

Huchman, H., Muller-Karger, F.E., and Walsh, J.J. 1994. Interpretation of the color signature of the Orinoco River plume. Journal of Geophysical Research 99: 7443-7455.

IOCCG. 1998. Minimum Requirements for an Operational Ocean-Colour Sensor for the Open Ocean. Morel, A. (ed.), Reports of the International Ocean-Colour Coordinating Group. No. 1, IOCCG, Dartmouth, Canada, 46pp.

IOCCG. 1999. Status and Plans for Satellite Ocean-Colour Missions: Considerations for Complementary Mission. Yoder, J. (ed.), Reports of the International Ocean-Colour Coordinating Group. No. 2, IOCCG, Dartmouth, Canada. 43pp.

IOCCG. 2000. Remote Sensing of Ocean Colour in Coastal, and Other Optically-Complex, Water. Sathyendranath, S. (ed.), Reports of the International Ocean-Colour Coordinating Group. No. 3, IOCCG, Dartmouth, Canada. 140pp.

IOCCG. 2004. Guide to the Creation and Use of Ocean-Colour, Level-3, Binned Data Products. Antoine, D. (ed.), Reports of the International Ocean-Colour Coordinating Group. No. 4, IOCCG, Dartmouth, Canada. 88p.

JAXA. 2003. GLI in-water algorithms. GLI Algorithm Description. Earth Observation Research and Application Center, Japan Aerospace Exploration Agency. 18pp.

Jerlov, N.G. 1976. Marine Optics. Elsevier Oceanography Series, 14 (2nd revised and enlarged edition of Optical Oceanography), Oxford, New York, 231pp.

Johnston, M.D. 1998. Seapol Integrated Studies of the Gulf of Thailand Volume 1. Southeast Asian Programme in Ocean Law, Policy and Management. Bangkok: Innomedia.

Kirk, J. T. O., 1980. Yellow substance and its contribution to the attenuation of photosynthetically active radiation in some island and coastal south eastern Australian waters. Australian Journal of Marine and Freshwater Research 27: 61-71.

Kirk, J.T.O. 1994. Light and Phytosynthesis in Aquatic Ecosystems. (2nd ed.), London: Cambridge University Press, 509pp.

Mishra, A. K. and Rao, D. P. 2002. Relationship between subsurface diffused reflectance and inherent optical properties in coastal waters. International Journal of Remote Sensing 23: 477-488.

Mobley, C. D. 1994. Light and Water: Radiative Transfer in Natural Waters. San Diego: Academic Press, 592pp.

Morel, A. and Prieur, L. 1977. Analysis of variations in ocean colour. American Society of Limnology and Oceanography 22: 709-722.

Nelson, J.R., and Guarda, S. 1995. Particulate and dissolved spectral absorption on the continental shelf of the southeastern United States. Journal of Geophysical Research 100: 8715-8732.

Nelson, N.B., and Siegel, D.A. 2002. Chromophoric DOM in the open ocean. Biogeochemistry of Marine Dissolved Organic Matter. Hansell, D.A. and Carlson, C.A. (ed.), Academic Press, San Diego, pp.547-578.

O'Reilly, J.E., Maritorena, S., Mitchell, B.G., Siegel, D.A., Carder, K.L., Garver, S.A., Kahru, M., and Mcclain, C.R. 1998. Ocean Color chlorophyll algorithm for SeaWiFS. Journal of Geophysical Research 103: 24937-24953.

Oonpan, S. 2003. Effects of tide and wind on simulated current in the Gulf of Thailand. A Thesis submitted in partial fulfillment of the requirements for the degree of Master of Science. Chulalongkorn University. 67pp.

Phaksopa, J. 2003. Storm surge in the gulf of Thailand generated by Typhoon Linda in 1997 using Princeton Ocean Model (POM). A Thesis submitted in partial fulfillment of the requirements for the degree of Master of Science. Chulalongkorn University. 82pp.

Pozdnyakov, D. and Grassl, H. 2003. Colour of Inland and Coastal Waters: A Methodology for Its Interpretation. Springer, 170pp.

Robinson, I. S. 2004. Measuring the Oceans from Space: The principles and methods of satellite oceanography. Springer-Praxis books in geophysical sciences. 699pp.

Shifrin, K.S. 1988. Physical Optics of Ocean Water. New York: American Institute of Physics, 285pp.

Siegel, D. A., Maritorena, S., Nelson, N.B., Hansell, D.A., and Lorenzi-Kayser, M. 2002. Global distribution and dynamics of colored dissolved and detrital organic materials. Journal of Geophysical Research 107: 10.1029/2001JC000965.

Singhruck, P. 2002. Numerical modeling of eddies in the gulf of Thailand comparing with satellite remote sensing data. A Thesis submitted in partial fulfillment of the requirements for the degree of Master of Science. Chulalongkorn University. 94pp.

Spinrad, R. W., Carder, K. L., and Perry, M. J. (Ed.) 1994. Ocean Optics. Oxford Monographs on Geology and Geophysics No.25, Oxford University Press, 283pp.

Strickland, J.D.H., and Parsons, T.R. 1972. A practical handbook of sea-water analysis. Bulletin 167 (second edition), Fisheries Research Board of Canada, 310pp.

Sturm, B. and Zibordi, G. 2002. SeaWiFS atmospheric correction by an approximate model and vicarious calibration. International Journal of Remote Sensing 23: 489-501.

UNEP. 1995. National Report of Thailand on the Formulation of a Transboundary Diagnostic Analysis and Preliminary Framework of a Strategic Action Programme for the South China Sea. East Asian Seas Regional Coordinating Unit, United Nations Environmental Programme. 117pp.

APPENDICES

APPENDIX A

Concentrations of three optically active constituents

Table A-1 Concentrations of three optically active constituents in cruise 1 (9-11 Oct 2003)

cruise 1	depth (m)	chlorophyll-a (mg/m^3)	suspended sediment (g/m^3)	coloured dissolved organic matter a412	a440	a443
station 1	0	1.37	1.40	0.175	0.115	0.117
	5	0.60	1.70	0.242	0.152	0.145
	10	4.54				
2	0	4.06	2.45	0.352	0.205	0.196
	5	4.53	2.20	0.276	0.159	0.147
	10	0.61				
3	0	1.06	1.50	0.449	0.286	0.260
	5	3.39	1.90	0.382	0.226	0.203
	9	2.50				
4	0	7.48	3.00	0.652	0.378	0.350
	5	7.03	2.70	0.456	0.281	0.263
	8	3.47				
5	0	9.96	5.00	0.705	0.421	0.387
	5	9.50	6.70	0.214	0.117	0.120
	10	2.58				
6	0	0.80	2.65	0.421	0.316	0.299
	5	2.24	1.65	0.193	0.127	0.113
	10	1.82				
7	0	1.04	1.57	0.461	0.276	0.267
	5	0.69	1.87	0.150	0.094	0.083
	10	2.73				
8	0	0.15	1.13	0.279	0.157	0.152
	5	0.31	0.83	0.290	0.180	0.157
	10	0.29				
9	0	0.13	0.55	0.106	0.064	0.058
	5	0.05	0.70	0.092	0.053	0.048
	10	0.16				
10	0	0.06	0.72	0.067	0.041	0.037
	5	0.09	0.56	0.074	0.041	0.046
	10	0.06				
11	0	0.19	1.10	0.150	0.097	0.090
	5	0.10	0.40	0.108	0.071	0.069
	10	0.08				
12	0	0.09	0.65	0.097	0.058	0.060
	5	0.10	0.65	0.078	0.055	0.044
	10	0.12				
13	0	0.05	0.80	0.081	0.051	0.048
	5	0.06	0.95	0.094	0.058	0.058
	10	0.21				
14	0	0.21	0.98	0.240	0.143	0.131
	5	0.18	1.58	0.152	0.099	0.088
	10	0.07				
15	0	0.13	0.66	0.076	0.055	0.048
	5	0.07	0.52	0.058	0.039	0.039
	10	0.24				
16	0	0.46	0.78	0.159	0.097	0.094
	5	0.14	0.68	0.159	nd	nd
	10	0.57				
17	0	0.69	1.95	0.161	0.115	0.111
	5	0.38	2.30	0.226	0.161	0.143
	10	2.41				

nd = no data

Table A-2 Concentrations of three optically active constituents in cruise 2 (4-6 Dec 2003)

cruise 2	depth (m)	chlorophyll-a (mg/m^3)	suspended sediment (g/m^3)	coloured dissolved organic matter a412	a440	a443
station 1	0	1.92	3.40	0.070	0.040	0.044
	5	0.89	2.10	0.006	-0.009	-0.005
	10	2.99				
2	0	0.63	2.80	0.050	0.022	0.021
	5	3.21	2.50	0.047	0.026	0.028
	10	0.57				
3	0	0.91	3.25	0.018	0.010	0.011
	5	1.33	4.50	0.036	0.018	0.018
	10	1.02				
4	0	7.68	2.85	0.193	0.122	0.121
	5	10.08	3.25	0.179	0.109	0.110
	9	3.82				
5	0	10.43	2.40	0.128	0.074	0.072
	5	8.91	2.30	0.166	0.097	0.093
	10	4.38				
6	0	6.79	3.65	0.311	0.191	0.183
	5	8.62	3.90	0.165	0.104	0.097
	10	3.97				
7	0	1.79	2.90	0.121	0.081	0.076
	5	1.89	2.60	0.130	0.079	0.081
	10	2.88				
8	0	3.30	3.10	0.078	0.052	0.051
	5	2.00	3.80	0.036	0.016	0.016
	10	2.00				
9	0	0.05	0.63	0.041	0.025	0.027
	5	0.06	0.83	0.073	0.059	0.057
	10	0.11				
10	0	0.06	0.90	0.045	0.031	0.031
	5	0.08	1.00	-0.007	-0.013	-0.013
	10	0.09				
11	0	0.34	2.63	0.042	0.032	0.026
	5	0.18	3.10	0.059	0.046	0.051
	10	0.17				
12	0	0.20	1.25	0.037	0.028	0.025
	5	0.24	1.15	0.035	0.017	0.013
	10	0.18				
13	0	0.06	1.08	0.075	0.059	0.057
	5	0.05	1.00	0.031	0.020	0.021
	10	0.05				
14	0	0.24	1.67	0.026	0.009	0.013
	5	0.37	1.87	0.013	-0.001	0.003
	10	0.39				
15	0	0.28	1.90	0.017	0.014	0.012
	5	0.40	1.40	0.014	0.006	0.006
	10	0.35				
16	0	0.70	1.20	0.025	0.016	0.018
	5	0.93	1.20	0.010	0.000	0.002
	10	0.81				
17	0	0.59	2.20	0.017	0.003	0.009
	5	0.92	2.10	0.065	0.047	0.044
	10	0.48				

nd = no data

Table A-3 Concentrations of three optically active constituents in cruise 3 (13-15 Jan 2004)

cruise 3	depth (m)	chlorophyll-a (mg/m^3)	suspended sediment (g/m^3)	coloured dissolved organic matter a412	a440	a443
station 1	0	1.45	5.00	0.092	0.059	0.058
	5	1.26	4.30	0.067	0.041	0.039
	10	1.25				
2	0	0.61	2.80	0.075	0.045	0.047
	5	0.72	2.33	0.102	0.069	0.066
	10	0.80				
3	0	1.48	3.70	0.089	0.051	0.045
	5	1.57	4.50	0.085	0.055	0.054
	10	1.50				
4	0	1.75	5.70	0.118	0.064	0.065
	5	3.74	8.20	0.095	0.044	0.045
	8	1.80				
5	0	1.14	0.95	0.139	0.084	0.081
	5	1.05	1.10	0.111	0.063	0.062
	10	1.74				
6	0	4.56	3.70	0.147	0.085	0.082
	5	3.27	3.20	0.121	0.070	0.062
	10	3.19				
7	0	0.43	0.73	0.063	0.032	0.035
	5	0.51	1.28	0.066	0.031	0.033
	10	1.01				
8	0	0.79	1.53	0.065	0.044	0.045
	5	0.82	1.70	0.025	0.002	0.006
	10	0.82				
9	0	0.58	1.50	0.020	0.010	0.009
	5	0.47	1.15	0.059	0.039	0.037
	10	0.36				
10	0	0.73	1.08	0.021	0.017	0.012
	5	0.70	1.05	0.014	0.006	0.006
	10	0.73				
11	0	0.94	3.00	0.036	0.023	0.023
	5	0.79	1.70	-0.036	-0.041	-0.045
	10	1.09				
12	0	0.78	1.10	-0.014	-0.020	-0.019
	5	0.87	1.00	0.043	0.033	0.034
	10	0.90				
13	0	2.21	0.90	-0.016	-0.024	-0.025
	5	0.51	1.10	0.041	0.023	0.021
	10	0.82				
14	0	0.41	1.20	0.018	0.003	-0.001
	5	0.42	1.30	0.022	0.005	0.000
	10	0.31				
15	0	0.42	1.15	0.020	0.006	0.005
	5	0.44	1.25	0.031	0.020	0.017
	10	0.50				
16	0	0.52	1.40	0.028	0.009	0.005
	5	0.57	1.55	0.020	0.007	0.007
	10	0.90				
17	0	1.01	2.40	0.028	-0.004	-0.007
	5	1.03	3.00	0.029	0.006	0.002
	10	2.10				

nd = no data

Table A-4 Concentrations of three optically active constituents in cruise 4 (12-15 May 2004)

cruise 4	depth (m)	chlorophyll-a (mg/m^3)	suspended sediment (g/m^3)	coloured dissolved organic matter a412	a440	a443
station 1	0	5.97	8.97	0.375	0.234	0.222
	5	3.97	1.25	0.515	0.342	0.331
	10	3.23				
2	0	1.54	0.84	0.394	0.268	0.259
	5	1.59	0.80	0.514	0.341	0.330
	10	6.17				
3	0	7.64	0.81	0.534	0.356	0.337
	5	6.07	0.73	0.647	0.454	0.435
	10	9.61				
4	0	1.68	0.78	0.344	0.226	0.212
	5	1.81	0.73	0.449	0.303	0.290
	8	10.48				
5	0	3.03	0.77	0.254	0.172	0.165
	5	1.88	0.36	0.294	0.203	0.195
	10	4.00				
6	0	6.40	1.50	0.269	0.189	0.180
	5	5.81	1.33	0.282	0.192	0.188
	10	5.78				
7	0	3.48	2.32	0.235	0.168	0.161
	5	3.61	2.38	0.317	0.225	0.216
	10	2.92				
8	0	1.69	0.61	0.195	0.138	0.135
	5	0.88	0.83	0.260	0.189	0.184
	10	0.94				
9	0	1.53	1.56	0.216	0.150	0.145
	5	1.58	1.06	0.192	0.139	0.136
	10	1.86				
10	0	nd	nd	nd	nd	nd
	5	nd	nd	nd	nd	nd
	10	nd				
11	0	0.96	0.57	0.207	0.149	0.145
	5	0.81	0.45	0.213	0.152	0.150
	10	0.81				
12	0	1.10	0.87	0.160	0.115	0.108
	5	1.11	0.93	0.180	0.134	0.131
	10	1.20				
13	0	1.06	0.31	0.160	0.117	0.115
	5	1.03	0.25	0.187	0.136	0.136
	10	1.18				
14	0	3.83	1.61	0.213	0.146	0.143
	5	3.58	1.69	0.216	0.151	0.147
	10	3.18				
15	0	nd	nd	nd	nd	nd
	5	nd	nd	nd	nd	nd
	10	nd				
16	0	0.70	0.23	0.261	0.174	0.166
	5	0.79	0.21	0.257	0.168	0.163
	10	0.76				
17	0	7.49	1.16	0.370	0.241	0.234
	5	9.36	1.62	0.572	0.389	0.370
	10	nd				

nd = no data

Table A-5 Concentrations of three optically active constituents in cruise 5 (7-10 Oct 2004)

cruise 5	depth (m)	chlorophyll-a (mg/m^3)	suspended sediment (g/m^3)	coloured dissolved organic matter a412	a440	a443
station 1	0	0.77	3.30	0.221	0.143	0.136
	5	0.64	3.30	0.516	0.366	0.351
	10	1.00				
2a	0	0.49	3.85	0.666	0.415	0.396
	5	0.36	3.70	0.627	0.391	0.376
	10	0.19				
2b	0	0.16	2.15	0.320	0.231	0.223
	5	0.16	2.10	0.225	0.154	0.149
	10	0.15				
3	0	0.66	1.50	0.704	0.457	0.437
	5	0.72	2.10	0.596	0.368	0.351
	11	0.33				
4	0	1.87	3.60	0.804	0.512	0.495
	5	0.32	2.80	0.307	0.197	0.188
	9	0.32				
5	0	0.39	2.20	0.634	0.392	0.375
	5	0.84	2.40	0.553	0.364	0.352
	10	0.33				
6	0	0.90	4.97	0.711	0.451	0.430
	5	1.20	4.30	0.495	0.329	0.315
	10	0.23				
7	0	0.25	2.13	0.652	0.414	0.392
	5	0.65	2.90	0.375	0.257	0.247
	10	0.50				
8	0	0.11	1.17	0.320	0.210	0.203
	5	0.08	0.70	0.171	0.119	0.113
	10	0.14				
9	0	0.08	0.80	0.127	0.096	0.089
	5	0.09	0.80	0.109	0.082	0.081
	10	0.05				
10	0	0.07	0.70	0.142	0.104	0.100
	5	0.04	0.80	0.120	0.087	0.087
	10	0.05				
11	0	0.04	0.88	0.158	0.119	0.117
	5	0.04	0.70	0.101	0.075	0.070
	10	0.06				
12	0	0.04	1.02	0.143	0.104	0.104
	5	0.04	0.80	0.121	0.087	0.086
	10	0.22				
13	0	0.06	0.73	0.168	0.125	0.120
	5	0.06	0.85	0.094	0.066	0.065
	10	0.03				
14	0	0.08	0.99	0.163	0.117	0.111
	5	0.06	0.85	0.145	0.102	0.095
	10	0.12				
15	0	0.11	1.10	0.184	0.141	0.133
	5	0.14	0.90	0.148	0.113	0.112
	10	0.15				
16	0	0.10	1.25	0.116	0.081	0.079
	5	0.13	1.55	0.171	0.120	0.116
	10	0.28				
17	0	0.54	5.15	0.180	0.123	0.118
	5	0.60	3.75	0.138	0.081	0.080
	10	0.55				

nd = no data

APPENDIX B

Remote sensing reflectance and diffuse attenuation coefficient

Table B-1 Remote sensing reflectance and diffuse attenuation coefficient in cruise 1 (9-11 Oct 2003)

Cruise 1	Remote Sensing Reflectance (Rrs)						Kd (490)
	412	443	490	520	565	670	
station 1	0.000964	0.001254	0.001822	0.002185	0.002667	0.000998	0.4723
2	0.001605	0.001948	0.002442	0.002414	0.003160	0.001300	0.6042
3	0.000825	0.001145	0.001868	0.002181	0.002734	0.000487	0.2472
4	0.000653	0.000894	0.001737	0.002397	0.003583	0.001235	0.5364
5	0.000676	0.001305	0.003144	0.004676	0.007221	0.002337	0.7078
6	0.000259	0.000559	0.001485	0.002279	0.003121	0.000691	0.3771
7	0.000989	0.001296	0.001906	0.002303	0.002809	0.001071	0.4549
8	0.000658	0.001289	0.002807	0.002584	0.002127	0.000525	0.1511
9	0.002005	0.002674	0.003872	0.002657	0.001735	0.000181	0.0838
10	0.003413	0.003908	0.004916	0.003210	0.001894	0.000258	0.0896
11	0.001586	0.002372	0.003867	0.003077	0.002202	0.000230	0.0491
12	0.004380	0.004624	0.005503	0.003605	0.002189	0.000162	0.0659
13	0.003698	0.004189	0.005115	0.003763	0.002534	0.000213	0.0822
14	0.001039	0.001816	0.004069	0.003757	0.003105	0.000463	0.1269
15	0.003405	0.004025	0.005667	0.004264	0.002884	0.000172	0.1264
16	0.001515	0.001983	0.003416	0.003287	0.002757	0.000404	0.1390
17	0.003490	0.003801	0.005093	0.004888	0.004260	0.000741	0.1689

Table B-2 Remote sensing reflectance and diffuse attenuation coefficient in cruise 2 (4-6 Dec 2003)

Cruise 2	Remote Sensing Reflectance (Rrs)						Kd (490)
	412	443	490	520	565	670	
station 1	0.008325	0.010271	0.015201	0.016084	0.016715	0.004876	0.3317
2	0.006950	0.008343	0.011612	0.010845	0.009577	0.001784	0.1931
3	0.007826	0.008666	0.011585	0.011366	0.010497	0.002516	0.2395
4	0.002315	0.002352	0.003161	0.003685	0.005032	0.001419	0.5703
5	0.001352	0.001555	0.002137	0.003057	0.003890	0.000925	0.3823
6	0.000548	0.000703	0.001216	0.002730	0.003792	0.000785	0.5263
7	0.004306	0.005294	0.007643	0.007812	0.007832	0.001543	0.2801
8	0.005413	0.006348	0.009266	0.009340	0.009092	0.001547	0.2346
9	0.004933	0.005729	0.007223	0.004938	0.003288	0.000560	0.1017
10	0.004983	0.005318	0.006383	0.004708	0.003277	0.000463	0.1111
11	0.007902	0.009120	0.012136	0.010578	0.008697	0.001260	0.1579
12	0.005577	0.006081	0.007594	0.005490	0.003678	0.000487	0.1094
13	0.004573	0.004809	0.005583	0.003796	0.002427	0.000304	0.0856
14	0.004625	0.005447	0.007782	0.006392	0.004927	0.000566	0.2916
15	0.005797	0.006440	0.008413	0.006884	0.005198	0.000734	0.1273
16	0.006704	0.007540	0.010005	0.008375	0.006466	0.000917	0.1426
17	0.005970	0.006975	0.010029	0.008564	0.006687	0.000871	0.1586

Table B-3 Remote sensing reflectance and diffuse attenuation coefficient in cruise 3 (13-15 Jan 2004)

Cruise 3	Remote Sensing Reflectance (Rrs)						Kd (490)
	412	443	490	520	565	670	
station 1	0.010765	0.013475	0.019007	0.019468	0.019395	0.006452	0.4169
2	0.007362	0.008634	0.011250	0.010327	0.009076	0.001718	0.1889
3	0.011385	0.013431	0.018251	0.019665	0.019973	0.005926	0.4630
4	0.020853	0.022304	0.027402	0.028750	0.028616	0.010173	0.6385
5	0.001252	0.001406	0.002264	0.002503	0.002419	0.000371	0.2093
6	0.002855	0.003274	0.004798	0.005119	0.004759	0.001339	0.2848
7	0.002697	0.003505	0.005618	0.004804	0.003692	0.000458	0.1377
8	0.006234	0.007250	0.009815	0.008551	0.007125	0.001138	0.1743
9	0.004045	0.004616	0.005982	0.004479	0.003160	0.000229	0.1026
10	0.004022	0.004178	0.005289	0.004284	0.003149	0.000489	0.1244
11	0.006859	0.007988	0.010468	0.009213	0.007560	0.001113	0.1634
12	0.004780	0.005222	0.006673	0.005537	0.004208	0.000680	0.1283
13	0.003827	0.003965	0.004889	0.003649	0.002433	0.000269	0.0957
14	0.005619	0.006666	0.008689	0.006981	0.005316	0.000640	0.1176
15	0.005182	0.005770	0.007388	0.005813	0.004209	0.000648	0.0560
16	0.006112	0.006822	0.008766	0.007385	0.005800	0.000902	0.1243
17	0.007010	0.007971	0.010740	0.010588	0.009575	0.001512	0.1931

Table B-4 Remote sensing reflectance and diffuse attenuation coefficient in cruise 4 (12-15 May 2004)

Cruise 4	Remote Sensing Reflectance (Rrs)						Kd (490)
	412	443	490	520	565	670	
station 1	0.003198	0.003830	0.005463	0.006528	0.007035	0.001738	0.3952
2	0.000604	0.001030	0.002049	0.002583	0.002936	0.000481	0.2095
3	0.001137	0.001426	0.002260	0.003484	0.004051	0.001002	0.3227
4	0.000882	0.001625	0.003810	0.004809	0.005323	0.000246	0.2237
5	0.002312	0.002603	0.003993	0.004625	0.004584	0.000467	0.2394
6	nd	nd	nd	nd	nd	nd	nd
7	0.006434	0.007303	0.010119	0.010758	0.011252	0.002750	0.3686
8	0.005642	0.006715	0.009192	0.008032	0.006702	0.001293	0.1734
9	0.006674	0.007962	0.011683	0.011715	0.011015	0.001911	0.2305
10	nd	nd	nd	nd	nd	nd	nd
11	0.004306	0.004944	0.006527	0.005303	0.004036	0.000318	0.0424
12	0.007148	0.007766	0.009534	0.008133	0.006516	0.000793	0.1880
13	0.005669	0.005983	0.007251	0.005950	0.004447	0.000407	0.3543
14	0.006076	0.007188	0.009993	0.010277	0.009918	0.002104	0.2453
15	nd	nd	nd	nd	nd	nd	nd
16	0.001744	0.002085	0.003231	0.003101	0.002465	0.000269	0.1657
17	0.010301	0.017571	0.010154	0.008985	0.004871	0.001121	0.4086

nd = no data

Table B-5 Remote sensing reflectance and diffuse attenuation coefficient in cruise 5 (7-10 Oct 2004)

Cruise 5	Remote Sensing Reflectance (Rrs)						Kd (490)
	412	443	490	520	565	670	
station 1	0.003173	0.002950	0.003703	0.004439	0.005142	0.001501	0.3215
2a	0.004645	0.007032	0.010498	0.012347	0.014018	0.008036	0.2721
2b	0.003107	0.003707	0.005494	0.005075	0.004337	0.000703	0.1364
3	0.001075	0.001735	0.002878	0.003520	0.004142	0.000956	0.2778
4	0.001107	0.001284	0.002231	0.003276	0.004918	0.002130	0.5992
5	0.001243	0.001501	0.002046	0.002554	0.003618	0.000831	0.5109
6	0.003838	0.004411	0.004926	0.005331	0.006397	0.002842	0.6979
7	0.002015	0.003261	0.005084	0.005567	0.005706	0.001840	0.4058
8	0.001568	0.002254	0.003477	0.002937	0.002328	0.000364	0.0983
9	0.004347	0.004528	0.005333	0.003665	0.002403	0.000321	0.0663
10	0.004448	0.004588	0.005297	0.003572	0.002264	0.000283	0.0921
11	0.005037	0.005108	0.005542	0.003877	0.002504	0.000260	0.0543
12	0.004876	0.004883	0.005425	0.003956	0.002651	0.000219	0.1105
13	0.004093	0.004224	0.004890	0.003540	0.002378	0.000336	0.0856
14	0.003634	0.004053	0.005195	0.003977	0.002835	0.000336	0.2320
15	0.004737	0.004852	0.006357	0.005183	0.003852	0.000415	0.1315
16	0.004783	0.005487	0.007341	0.006676	0.005511	0.000786	0.2079
17	0.009383	0.010290	0.014567	0.015577	0.016172	0.004278	0.3786

station 2a = inside river plume front

station 2b = outside river plume front

APPENDIX C

Nutrients and other oceanographic parameters

Table C-1 Nutrients and other oceanographic parameters in cruise 1 (9-11 Oct 2003)

cruise 1	depth (m)	ammonia µM	nitrite µM	nitrate µM	phosphate µM	silicate µM	temperature (°c)	salinity (psu)	DO (ml/l)	pH
station 1	0	11.39	0.41	0.09	0.59	15.61	29.46	29.99	5.33	8.16
	5	10.00	0.49	0.08	0.57	17.19	29.53	30.35	4.25	8.14
	10	11.59	0.69	0.16	0.55	17.54	29.44	32.03	3.32	8.06
2	0	11.19	0.08	0.06	0.74	15.61	29.49	27.85	6.03	8.19
	5	11.99	0.06	1.93	2.63	12.63	29.53	29.65	4.39	8.07
	10	10.99	1.87	0.40	0.47	14.91	29.49	31.70	2.26	8.00
	14	10.40	2.89	0.59	0.45	15.26	29.39	32.07	3.31	8.10
3	0	9.60	0.08	0.00	0.60	12.45	30.42	27.45	6.86	8.40
	5	10.20	0.08	0.03	0.55	13.50	29.81	27.73	7.20	8.41
	9	14.39	0.06	0.00	1.64	23.67	29.66	29.65	1.56	7.92
4	0	9.20	0.04	0.17	1.37	10.87	31.20	22.19	7.50	8.59
	5	8.60	0.06	0.00	0.60	9.82	29.93	27.86	4.70	8.23
	8	10.20	0.08	0.00	1.01	18.41	29.68	30.95	2.18	7.93
5	0	7.00	0.06	0.00	1.35	18.06	31.28	20.15	9.96	8.65
	5	9.00	0.04	0.00	0.20	13.15	29.75	31.09	7.89	8.39
	10	8.80	2.85	0.63	0.92	17.71	29.67	31.95	2.21	7.96
	15	9.00	3.38	0.81	0.86	19.47	29.67	32.03	0.41	7.86
6	0	7.60	0.06	0.00	0.88	18.59	31.00	22.92	5.35	8.47
	5	9.20	0.06	0.00	0.39	15.61	30.04	30.51	4.57	8.37
	10	10.20	2.16	0.47	0.66	18.41	29.67	31.77	2.82	8.15
	17	8.80	0.69	0.09	0.39	13.68	29.66	32.35	0.74	7.94
7	0	6.80	0.04	0.00	0.64	16.83	30.05	24.01	4.70	8.57
	5	10.60	0.06	0.01	0.20	12.63	29.85	31.58	4.68	8.40
	10	11.59	0.33	1.24	0.25	12.98	29.67	32.47	3.54	8.25
	19	9.80	1.55	0.01	0.45	18.06	29.64	32.71	2.14	8.10
8	0	10.40	0.08	0.00	0.49	13.15	29.53	28.06	4.26	8.46
	5	7.60	0.04	0.00	0.43	11.57	29.35	31.20	3.55	8.38
	10	9.60	0.04	0.00	0.18	7.37	29.56	32.06	3.40	8.30
	20	10.60	0.20	0.22	0.25	15.08	29.76	32.69	2.45	8.23
9	0	10.40	0.04	0.03	0.20	6.14	29.65	29.11	1.45	8.41
	5	10.20	0.04	0.03	0.16	5.26	29.75	31.77	1.83	8.32
	10	9.40	0.04	0.00	0.14	5.09	29.73	31.91	1.97	8.31
	22	10.40	0.04	0.00	0.18	7.89	29.60	32.42	2.30	8.30
10	0	8.00	0.04	0.03	0.12	4.56	30.50	31.55	4.39	8.29
	5	7.60	0.04	0.00	0.12	4.56	30.33	31.57	4.92	8.30
	10	11.99	0.06	0.00	0.21	10.00	29.84	31.64	4.54	8.30
	27	8.20	0.04	0.00	0.10	6.31	29.47	32.23	4.37	8.29
11	0	9.60	0.04	0.00	0.21	9.29	29.54	30.17	3.11	8.37
	5	9.80	0.04	0.00	0.18	7.37	29.60	31.29	3.16	8.33
	10	9.60	0.06	0.00	0.21	6.14	29.71	32.49	3.21	8.29
	26	10.40	0.53	0.25	0.25	15.43	29.82	33.01	2.74	8.19
12	0	10.00	0.04	0.00	0.16	4.91	30.28	32.26	2.66	8.30
	5	10.00	0.06	0.00	0.18	5.09	29.79	32.44	2.85	8.30
	10	10.00	0.04	0.03	0.20	5.61	29.70	32.50	3.13	8.29
	23	9.80	0.04	0.00	0.18	7.72	29.47	32.71	2.83	8.28
13	0	8.00	0.04	0.00	0.12	4.38	30.41	31.34	2.52	8.30
	5	8.00	0.04	0.00	0.14	4.91	29.91	31.53	2.58	8.30
	10	8.40	0.04	0.03	0.16	5.09	29.67	31.89	2.67	8.30
	36	8.60	0.04	0.00	0.14	5.61	29.25	33.09	2.59	8.26
14	0	9.60	0.06	0.08	0.41	15.43	29.95	28.36	1.17	8.38
	5	9.20	0.04	0.00	0.25	11.57	29.66	31.51	1.26	8.30
	10	9.40	0.04	0.00	0.12	5.61	29.51	31.67	1.51	8.30
	18	10.99	0.04	0.03	0.18	10.52	29.44	32.70	2.37	8.28
15	0	11.79	0.06	0.15	0.14	7.54	30.14	31.24	1.39	8.31
	5	10.99	0.04	0.00	0.12	5.61	29.74	31.57	1.32	8.31
	10	10.60	0.04	0.00	0.12	6.66	29.76	31.90	1.56	8.30
	15	11.19	0.04	0.00	0.14	8.94	29.99	32.08	1.81	8.29
16	0	9.00	0.04	0.03	0.29	13.85	30.75	28.95	0.41	8.25
	5	10.00	0.04	0.00	0.27	14.73	30.31	31.20	2.82	8.27
	10	nd	nd	nd	nd	nd	29.75	31.03	3.39	8.34
	19	8.20	0.08	0.20	0.21	10.17	29.47	32.08	5.81	8.27
17	0	8.00	0.04	0.00	0.16	9.12	30.14	28.15	5.32	8.27
	5	8.80	0.04	0.00	0.20	9.12	30.10	30.29	3.46	8.30
	10	8.40	0.04	0.00	0.18	8.94	29.80	30.47	4.68	8.31
	26	9.80	0.16	0.05	0.23	12.10	29.41	31.05	3.29	8.15

nd = no data

Table C-2 Nutrients and other oceanographic parameters in cruise 2 (4-6 Dec 2003)

cruise 2	depth (m)	ammonia µM	nitrite µM	nitrate µM	phosphate µM	silicate µM	temperature (°c)	salinity (psu)	DO (ml/l)	pH
station 1	0	9.00	0.04	0.17	0.20	5.61	27.55	31.34	8.12	8.37
	5	8.40	0.06	0.05	0.20	6.31	27.58	31.36	8.04	8.40
	10	9.80	0.08	0.00	0.20	6.31	27.59	31.36	8.05	8.41
2	0	10.60	0.08	0.06	0.20	7.19	27.87	31.30	8.37	8.40
	5	10.00	0.06	0.01	0.18	6.14	27.90	31.30	8.24	8.41
	10	11.79	0.06	0.15	0.18	6.84	27.90	31.30	8.25	8.41
	15	9.40	0.04	0.07	0.18	5.44	27.89	31.30	8.24	8.41
3	0	9.20	0.04	0.00	0.18	7.37	27.71	31.36	4.10	8.39
	5	11.59	0.04	0.07	0.20	6.49	27.72	31.36	4.50	8.41
	10	9.20	0.04	0.00	0.18	6.49	27.68	31.36	1.48	8.42
4	0	10.00	0.04	0.17	0.20	9.47	27.60	30.61	10.58	8.45
	5	10.00	0.04	0.00	0.20	8.24	27.22	30.65	11.29	8.48
	9	10.40	0.04	0.00	0.18	7.37	27.20	30.70	10.15	8.45
5	0	9.00	0.06	0.00	0.39	15.61	27.99	30.00	9.62	8.45
	5	10.40	0.04	0.00	0.35	13.85	27.69	30.69	10.45	8.47
	10	10.79	0.06	0.00	0.25	11.75	27.79	31.06	9.21	8.42
	15	10.40	0.04	0.03	0.27	11.92	27.76	31.19	8.67	8.41
6	0	9.20	0.04	0.00	0.64	20.69	28.04	29.05	9.60	8.42
	5	12.99	0.08	0.20	0.43	14.55	27.94	30.65	9.27	8.41
	10	10.79	0.08	0.06	0.31	11.22	27.92	30.93	8.30	8.38
	15	11.39	0.08	0.06	0.35	13.85	28.01	31.11	7.56	8.36
7	0	9.60	0.04	0.07	0.21	11.40	27.86	31.17	8.32	8.40
	5	9.20	0.04	0.00	0.23	11.92	27.87	31.17	8.33	8.42
	10	8.60	0.04	0.00	0.20	10.87	27.87	31.17	8.35	8.42
	18	11.99	0.04	0.03	0.23	11.75	27.88	31.17	8.36	8.43
8	0	10.60	0.08	0.03	0.20	5.09	28.01	31.30	8.57	8.43
	5	8.40	0.04	0.00	0.16	4.73	28.00	31.30	5.59	8.44
	10	11.59	0.08	0.00	0.21	4.73	28.01	31.30	5.59	8.44
	23	10.40	0.06	0.01	0.20	4.56	27.93	31.30	8.48	8.44
9	0	9.00	0.04	0.00	0.16	7.19	28.22	31.24	8.09	8.29
	5	9.20	0.04	0.00	0.12	6.66	28.23	31.24	8.09	8.37
	10	10.20	0.04	0.07	0.14	7.54	28.23	31.25	8.10	8.39
	20	10.60	0.04	0.03	0.20	8.77	28.20	31.34	8.04	8.40
10	0	10.00	0.04	0.00	0.16	7.89	28.65	31.26	8.23	8.40
	5	7.20	0.04	0.00	0.16	7.19	28.65	31.27	8.20	8.41
	10	9.20	0.08	0.00	0.12	7.01	28.64	31.27	8.21	8.41
	25	9.00	0.04	0.10	0.14	6.66	28.52	31.26	8.14	8.41
11	0	10.99	0.02	0.00	0.14	7.72	28.41	31.25	8.34	8.41
	5	10.40	0.02	0.05	0.18	7.37	28.41	31.25	8.30	8.42
	10	15.19	0.08	0.10	0.21	10.00	28.35	31.25	8.30	8.42
	26	10.20	0.04	0.00	0.20	7.72	28.27	31.25	8.27	8.42
12	0	9.80	0.04	0.00	0.16	7.72	28.41	31.25	8.34	8.41
	5	10.20	0.04	0.07	0.16	8.77	28.41	31.25	8.30	8.42
	10	10.99	0.04	0.07	0.14	8.42	28.35	31.25	8.30	8.42
	24	10.40	0.04	0.00	0.16	7.37	28.27	31.25	8.27	8.42
13	0	9.00	0.04	0.00	0.16	7.72	28.76	31.19	8.30	8.41
	5	8.60	0.04	0.00	0.16	6.66	28.75	31.19	8.25	8.42
	10	9.20	0.04	0.00	0.16	6.84	28.63	31.18	8.27	8.42
	35	8.80	0.02	0.00	0.12	6.49	28.59	31.18	8.19	8.42
14	0	7.40	0.02	0.02	0.12	6.84	27.98	31.37	8.39	8.40
	5	10.99	0.04	0.03	0.25	8.59	27.98	31.37	8.37	8.41
	10	13.79	0.04	0.03	0.21	8.94	27.98	31.37	8.33	8.41
	19	10.60	0.04	0.00	0.14	7.37	27.97	31.37	8.30	8.41
15	0	10.40	0.04	0.00	0.18	9.12	28.26	31.28	8.38	8.37
	5	10.00	0.02	0.02	0.14	8.24	28.26	31.27	8.29	8.40
	10	11.19	0.04	0.03	0.16	9.29	28.53	31.28	8.27	8.41
	15	10.99	0.04	0.00	0.18	8.94	28.21	31.29	8.22	8.41
16	0	9.00	0.04	0.03	0.16	8.59	28.12	31.41	8.56	8.40
	5	10.20	0.04	0.03	0.20	8.94	28.09	31.41	8.50	8.40
	10	9.40	0.04	0.03	0.16	7.89	28.01	31.41	8.50	8.41
	19	9.40	0.04	0.00	0.20	8.07	27.92	31.42	8.40	8.41
17	0	10.00	0.04	0.00	0.20	7.19	28.22	31.41	8.56	8.38
	5	11.19	0.04	0.07	0.20	6.66	28.22	31.42	8.54	8.39
	10	9.40	0.02	0.00	0.16	6.66	28.16	31.42	8.54	8.39

nd = no data

Table C-3 Nutrients and other oceanographic parameters in cruise 3 (13-15 Jan 2004)

cruise 3	Depth	ammonia	nitrite	nitrate	phosphate	silicate	temperature	salinity	DO	pH
	(m)	μM	μM	μM	μM	μM	(°c)	(psu)	(ml/l)	
station 1	0	9.40	0.04	0.07	0.23	4.91	26.38	31.70	8.60	8.41
	5	9.80	0.04	0.03	0.21	4.73	26.41	31.72	8.42	8.46
	10	9.40	0.04	0.10	0.21	4.73	26.41	31.72	8.40	8.47
2	0	10.00	0.06	0.01	0.18	8.59	26.62	31.79	8.49	8.39
	5	10.00	0.08	0.00	0.20	8.59	26.57	31.80	8.39	8.42
	10	7.40	0.04	0.07	0.14	6.84	26.55	31.79	8.38	8.43
	15	10.79	0.06	0.01	0.20	8.42	26.55	31.80	8.31	8.43
3	0	9.00	0.41	0.37	0.29	9.47	26.56	31.24	2.19	8.40
	5	9.80	0.08	0.06	0.27	9.29	26.50	31.52	3.66	8.42
	10	10.99	0.08	0.06	0.25	10.52	26.52	31.61	6.54	8.43
4	0	10.60	0.08	0.17	0.35	12.28	26.88	30.80	7.12	8.26
	5	12.99	0.10	0.11	0.45	12.80	26.36	30.86	7.01	8.30
	8	12.59	0.12	0.06	0.41	11.75	26.31	30.92	6.70	8.30
5	0	7.00	0.12	0.00	0.29	8.77	26.51	30.24	9.06	8.48
	5	7.20	0.06	0.00	0.27	8.77	26.14	30.28	9.12	8.48
	10	8.80	0.06	0.00	0.27	7.89	26.05	30.33	9.04	8.49
	15	9.80	0.08	0.06	0.29	13.68	26.13	31.22	7.13	8.39
6	0	12.79	0.16	1.12	0.68	22.97	26.47	30.16	8.72	8.40
	5	9.60	0.49	0.22	0.39	17.36	26.32	30.64	8.71	8.46
	10	9.20	0.29	0.00	0.25	11.05	26.14	30.87	8.58	8.47
	15	11.79	0.04	0.39	0.39	17.54	26.20	31.32	7.40	8.42
7	0	8.00	0.16	0.00	0.20	11.05	26.25	31.16	8.75	8.47
	5	5.40	0.04	0.00	0.18	8.94	26.27	31.18	8.75	8.48
	10	8.80	0.04	0.07	0.20	10.00	26.34	31.40	8.56	8.47
	18	11.19	0.06	0.05	0.25	14.03	26.35	31.55	8.04	8.45
8	0	8.00	0.08	0.00	0.16	7.37	26.83	32.01	8.76	8.46
	5	7.80	0.04	0.03	0.14	8.42	26.82	32.01	8.61	8.48
	10	8.00	0.04	0.03	0.16	7.72	26.82	32.01	8.57	8.48
	24	8.00	0.04	0.03	0.16	7.01	26.83	32.01	8.54	8.48
9	0	10.99	0.04	0.10	0.20	6.84	27.08	32.26	8.50	8.42
	5	7.60	0.08	0.06	0.16	6.31	27.08	32.26	8.45	8.44
	10	10.99	0.04	0.03	0.20	7.01	27.09	32.27	8.43	8.44
	20	8.80	0.04	0.03	0.16	5.79	27.10	32.26	8.40	8.44
10	0	10.00	0.04	0.03	0.16	6.66	27.40	32.17	8.53	8.45
	5	9.40	0.04	0.03	0.16	6.49	27.28	32.23	8.54	8.46
	10	9.60	0.04	0.00	0.14	6.31	27.18	32.24	8.53	8.47
	26	8.80	0.04	0.03	0.14	5.61	27.12	32.26	8.38	8.46
11	0	9.80	0.04	0.07	0.16	7.37	27.03	32.14	8.68	8.44
	5	12.99	0.08	0.03	0.20	9.29	27.04	32.13	8.54	8.46
	10	9.40	0.08	0.00	0.16	6.49	27.03	32.14	8.52	8.46
	28	9.40	0.08	0.00	0.12	6.31	27.01	32.14	8.44	8.46
12	0	8.20	0.06	0.00	0.18	6.31	27.19	32.31	8.53	8.46
	5	9.80	0.08	0.00	0.21	5.96	27.14	32.32	8.52	8.46
	10	8.60	0.08	0.00	0.18	5.79	27.09	32.31	8.51	8.46
	24	7.00	0.08	0.06	0.16	5.96	27.07	32.31	8.39	8.47
13	0	9.20	0.08	0.06	0.14	5.44	27.68	32.21	8.57	8.47
	5	8.20	0.08	0.03	0.14	4.73	27.22	32.28	8.62	8.47
	10	9.40	0.08	0.03	0.16	5.44	27.30	32.39	8.53	8.47
	36	10.60	0.08	0.13	0.16	6.14	27.23	32.42	8.33	8.46
14	0	7.20	0.08	0.06	0.16	8.42	26.80	31.92	8.71	8.44
	5	11.19	0.06	0.08	0.20	11.22	26.76	31.90	8.68	8.45
	10	10.00	0.08	0.06	0.20	9.47	26.75	31.90	8.66	8.45
	19	9.20	0.04	0.07	0.16	10.52	26.75	31.91	8.61	8.45
15	0	10.00	0.08	0.00	0.16	8.59	27.47	32.17	8.48	8.43
	5	8.00	0.06	0.05	0.12	6.84	27.16	32.16	8.50	8.44
	10	9.00	0.04	0.10	0.14	7.01	27.07	32.15	8.50	8.44
	15	8.20	0.04	0.07	0.12	6.84	27.05	32.15	8.43	8.45
16	0	8.00	0.04	0.10	0.12	8.59	27.23	31.96	8.60	8.42
	5	8.00	0.04	0.17	0.12	8.59	26.81	31.95	8.63	8.44
	10	8.40	0.04	0.17	0.12	8.59	26.78	31.95	8.61	8.44
	20	8.00	0.04	0.17	0.12	8.42	26.76	31.95	8.51	8.44
17	0	9.20	0.04	0.10	0.16	5.79	27.48	31.90	8.59	8.41
	5	10.40	0.04	0.03	0.21	5.79	26.73	31.88	8.69	8.44
	10	8.60	0.04	0.03	0.18	5.44	26.64	31.88	8.62	8.44

nd = no data

Table C-4 Nutrients and other oceanographic parameters in cruise 4 (12-15 May 2004)

cruise 4	Depth (m)	ammonia µM	nitrite µM	nitrate µM	phosphate µM	silicate µM	temperature (°c)	salinity (psu)	DO (ml/l)	pH
station 1	0	10.60	3.91	1.91	1.11	19.29	30.80	31.01	6.52	8.14
	5	10.99	3.59	1.81	1.01	19.64	30.76	31.00	6.32	8.42
	10	11.99	2.57	1.41	0.84	17.89	30.57	31.04	6.03	8.41
2	0	7.40	0.00	0.14	0.23	21.92	30.79	30.60	6.59	8.64
	5	10.00	0.06	0.29	0.31	23.15	30.79	30.60	6.50	8.64
	10	12.99	0.08	0.63	0.39	14.55	30.70	31.58	6.04	8.59
	15	11.19	0.08	0.56	0.43	15.08	30.70	32.12	4.09	8.45
3	0	5.60	0.04	0.14	0.29	25.43	30.66	30.01	6.64	8.60
	5	7.40	0.04	0.17	0.35	25.60	30.65	30.01	6.65	8.62
	10	9.40	0.24	0.54	0.41	17.36	30.79	31.19	5.25	8.51
4	0	8.00	0.04	0.10	0.18	22.45	30.74	30.39	6.88	8.57
	5	6.00	0.02	0.12	0.18	16.13	30.55	30.36	6.84	8.56
	8	9.60	0.12	0.34	0.43	19.82	30.76	31.57	5.93	8.48
5	0	8.80	0.06	0.15	0.18	14.03	30.73	32.25	6.41	8.53
	5	9.00	0.04	0.24	0.21	14.55	30.73	32.26	6.43	8.54
	10	8.40	0.02	0.19	0.23	9.64	30.68	32.32	6.34	8.54
	14	9.40	0.08	0.98	0.33	13.85	30.85	32.68	5.53	8.50
6	0	8.60	0.04	0.24	0.18	12.98	30.72	32.56	6.21	8.55
	5	9.00	0.08	0.13	0.21	15.08	30.73	32.57	6.33	8.57
	10	5.60	0.04	0.17	0.18	7.89	30.76	32.67	6.22	8.56
	15	9.80	0.12	0.30	0.23	12.28	30.81	32.86	5.50	8.53
7	0	6.20	0.04	0.17	0.16	4.21	30.45	32.97	6.04	8.56
	5	8.00	0.04	0.17	0.16	7.19	30.46	32.98	5.97	8.57
	10	8.80	0.04	0.39	0.21	6.14	30.46	32.98	5.95	8.57
	16	8.80	0.04	0.31	0.18	6.31	30.46	32.98	5.92	8.57
8	0	9.00	0.06	0.44	0.18	10.17	30.35	32.91	6.10	8.52
	5	5.40	0.04	0.17	0.12	6.84	30.36	32.91	6.03	8.55
	10	7.00	0.04	0.31	0.16	9.47	30.36	32.91	6.01	8.55
	23	8.40	0.04	0.17	0.18	10.87	30.35	32.91	5.97	8.55
9	0	8.20	0.04	0.17	0.20	8.24	30.26	32.77	6.25	8.55
	5	10.00	0.04	0.31	0.20	8.94	30.27	32.78	6.23	8.56
	10	7.60	0.04	0.17	0.14	6.66	30.28	32.78	6.22	8.56
	20	8.00	0.04	0.17	0.16	8.24	30.28	32.78	6.18	8.56
10	0	nd	nd	nd	nd	nd	30.35	32.67	6.09	8.53
	5	nd	nd	nd	nd	nd	30.37	32.68	6.02	8.54
	10	nd	nd	nd	nd	nd	30.38	32.68	6.01	8.54
	28	nd	nd	nd	nd	nd	30.38	32.68	5.96	8.54
11	0	7.80	0.04	0.24	0.16	10.52	30.25	32.73	6.59	8.53
	5	7.80	0.04	0.24	0.16	9.12	30.23	32.74	6.49	8.54
	10	10.00	0.04	0.39	0.23	11.92	30.21	32.74	6.43	8.54
	27	9.40	0.04	0.24	0.18	12.45	30.19	32.75	6.29	8.53
12	0	6.60	0.04	0.24	0.16	12.63	30.58	32.63	6.68	8.53
	5	7.00	0.04	0.14	0.16	12.45	30.41	32.62	6.59	8.53
	10	9.60	0.04	0.17	0.16	12.28	30.32	32.63	6.56	8.53
	23	8.20	0.04	0.10	0.16	13.50	30.29	32.64	6.44	8.53
13	0	7.40	0.04	0.17	0.16	8.42	30.74	32.74	6.52	8.53
	5	7.00	0.04	0.17	0.16	9.47	30.71	32.74	6.53	8.53
	10	8.80	0.04	0.24	0.21	10.00	30.47	32.74	6.54	8.54
	35	11.59	0.04	0.46	0.35	10.17	30.42	32.75	6.33	8.53
14	0	8.60	0.04	0.31	0.18	10.17	30.33	32.42	6.46	8.54
	5	8.40	0.04	0.31	0.20	10.17	30.43	32.42	6.35	8.56
	10	7.20	0.02	0.33	0.16	9.29	30.30	32.42	6.29	8.55
	19	5.60	0.04	0.17	0.14	8.77	30.30	32.42	6.21	8.55
15	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
16	0	7.40	0.04	0.31	0.20	14.20	30.58	31.80	6.29	8.54
	5	7.40	0.04	0.24	0.20	13.50	30.49	31.80	6.39	8.55
	10	8.80	0.04	0.46	0.23	13.50	30.43	31.96	6.34	8.53
	18	6.80	0.04	0.31	0.14	10.52	30.65	32.55	6.14	8.51
17	0	6.80	0.04	0.39	0.29	13.15	30.86	30.80	7.38	8.60
	5	8.00	0.04	0.46	0.39	13.33	30.62	30.80	7.91	8.63
	10	6.80	0.06	0.44	0.23	14.55	30.72	31.37	7.22	8.57

nd = no data

Table C-5 Nutrients and other oceanographic parameters in cruise 5 (7-10 Oct 2004)

cruise 5	Depth (m)	ammonia μM	nitrite μM	nitrate μM	phosphate μM	silicate μM	temperature (°c)	salinity (psu)	DO (ml/l)	pH
station 1	0	10.32	0.48	0.36	0.53	11.94	29.54	32.19	4.86	8.42
	5	9.74	0.48	0.36	0.40	11.94	29.38	32.21	4.78	8.49
	10	12.04	3.85	0.63	0.60	15.92	29.41	32.45	4.49	8.50
2a	0	13.76	2.05	6.93	1.59	43.21	29.19	24.65	5.39	8.62
	5	13.18	1.81	6.05	1.39	37.52	29.48	32.27	5.21	8.60
	10	9.17	0.18	0.10	0.40	6.82	29.48	32.38	5.20	8.64
	15	11.46	0.96	2.40	0.66	18.76	29.48	32.50	4.74	8.63
2b	0	6.31	0.24	0.04	0.27	5.69	29.52	32.35	5.60	8.58
	5	7.45	0.24	0.32	0.33	6.82	29.49	32.40	5.57	8.60
	10	8.02	0.24	0.18	0.33	9.67	29.54	32.49	5.52	8.62
	15	7.45	0.12	0.16	0.33	6.25	29.51	32.53	5.34	8.63
3	0	11.46	1.08	3.12	1.06	21.04	29.86	24.33	6.32	8.63
	5	5.73	1.93	1.16	0.53	10.23	29.53	30.96	4.68	8.60
	11	9.17	0.84	2.80	0.93	18.19	29.39	31.74	3.40	8.50
4	0	8.02	0.18	0.10	0.53	4.55	30.95	23.67	8.09	8.87
	5	9.74	0.12	0.02	0.50	4.55	29.49	30.49	6.54	8.78
	9	9.74	0.12	0.02	0.53	5.69	29.59	31.07	3.96	8.60
5	0	8.60	0.12	0.30	1.19	1.14	30.99	23.75	7.87	8.97
	5	9.17	0.18	0.00	0.93	1.71	29.70	30.15	2.44	8.66
	10	13.18	1.32	3.72	1.09	34.11	29.75	32.23	0.84	8.41
	16	13.18	1.57	2.64	0.99	34.11	29.68	32.44	0.39	8.32
6	0	10.32	0.36	0.76	1.06	3.41	31.70	22.84	7.90	8.86
	5	14.33	0.36	1.04	1.46	2.84	29.74	29.54	4.86	8.77
	10	10.32	1.32	4.29	0.93	35.25	29.65	32.61	1.68	8.46
	16	10.32	0.72	2.08	1.09	14.78	29.60	32.88	1.07	8.35
7	0	6.88	0.12	0.02	0.60	1.14	29.47	24.51	6.59	8.90
	5	8.60	0.30	0.00	0.60	18.19	29.89	30.41	3.48	8.63
	10	6.88	0.36	0.20	0.53	25.58	29.60	33.00	2.17	8.51
	17	10.32	6.62	2.07	0.93	37.52	29.58	33.23	1.48	8.40
8	0	10.89	0.18	0.66	0.60	6.25	29.57	29.56	5.75	8.86
	5	12.61	0.24	0.32	0.60	7.39	29.37	32.33	5.60	8.65
	10	9.17	0.12	0.00	0.27	6.25	29.26	32.50	5.57	8.65
	23	11.46	1.20	0.20	0.53	3.41	29.51	33.38	4.63	8.59
9	0	9.74	0.12	0.16	0.20	5.12	29.41	32.32	5.29	8.66
	5	10.32	0.12	0.30	0.33	4.55	29.46	32.33	5.32	8.68
	10	10.32	0.12	0.30	0.27	5.69	29.63	32.81	5.28	8.68
	21	8.60	0.18	0.10	0.30	5.69	29.59	33.04	5.07	8.65
10	0	8.02	0.12	0.02	0.27	6.25	30.74	32.21	5.69	8.63
	5	6.88	0.12	0.02	0.20	5.69	29.94	32.25	5.78	8.66
	10	8.02	0.12	0.02	0.20	5.69	29.80	32.29	5.76	8.67
	26	7.45	0.18	0.10	0.27	6.82	29.59	32.73	5.52	8.65
11	0	6.88	0.12	0.02	0.20	5.12	29.56	32.67	5.63	8.61
	5	7.45	0.12	0.16	0.20	5.12	29.45	32.68	5.66	8.65
	10	7.45	0.12	0.16	0.23	3.41	29.32	32.82	5.65	8.66
	26	7.45	0.12	0.16	0.27	1.14	29.53	33.56	4.97	8.60
12	0	8.02	0.12	0.16	0.27	6.82	30.93	32.75	5.59	8.61
	5	8.60	0.18	0.10	0.27	6.82	29.70	32.85	5.66	8.66
	10	6.88	0.24	0.04	0.33	5.12	29.72	33.04	5.59	8.66
	24	6.88	0.18	0.10	0.27	3.98	29.69	33.11	5.46	8.65
13	0	7.45	0.12	0.16	0.23	7.39	30.86	31.84	5.66	8.63
	5	8.02	0.12	0.30	0.27	6.82	29.78	32.00	5.73	8.66
	10	9.17	0.12	0.30	0.27	8.53	29.74	32.42	5.67	8.66
	35	7.45	0.12	0.30	0.27	7.39	29.63	33.09	5.16	8.62
14	0	8.60	0.12	0.30	0.33	6.82	29.70	32.55	5.52	8.64
	5	8.60	0.18	0.24	0.33	6.82	29.67	32.56	5.53	8.65
	10	8.60	0.18	0.10	0.33	6.25	29.72	32.79	5.47	8.65
	17	8.60	0.12	0.02	0.27	6.82	29.73	32.98	5.17	8.63
15	0	8.60	0.24	0.04	0.33	4.55	29.81	32.20	5.65	8.56
	5	8.60	0.18	0.10	0.27	5.12	29.54	32.25	5.71	8.60
	10	8.60	0.18	0.10	0.27	6.25	29.51	32.30	5.71	8.61
	15	8.02	0.18	0.10	0.33	9.67	29.59	32.67	5.46	8.60
16	0	8.60	0.18	0.10	0.33	10.80	30.09	32.68	5.13	8.53
	5	6.88	0.18	0.00	0.33	10.23	29.86	32.68	5.12	8.57
	10	9.74	0.24	0.04	0.33	15.35	29.48	32.65	5.07	8.58
	20	8.60	0.72	0.00	0.33	13.64	29.43	32.67	4.90	8.58
17	0	7.45	0.24	0.00	0.30	10.80	29.65	32.43	5.70	8.54
	5	6.31	0.24	0.00	0.27	9.67	29.62	32.46	5.74	8.60
	10	5.73	0.24	0.04	0.33	10.23	29.46	32.48	5.62	8.62

nd = no data

APPENDIX D

Proportions of organic and inorganic suspended sediments

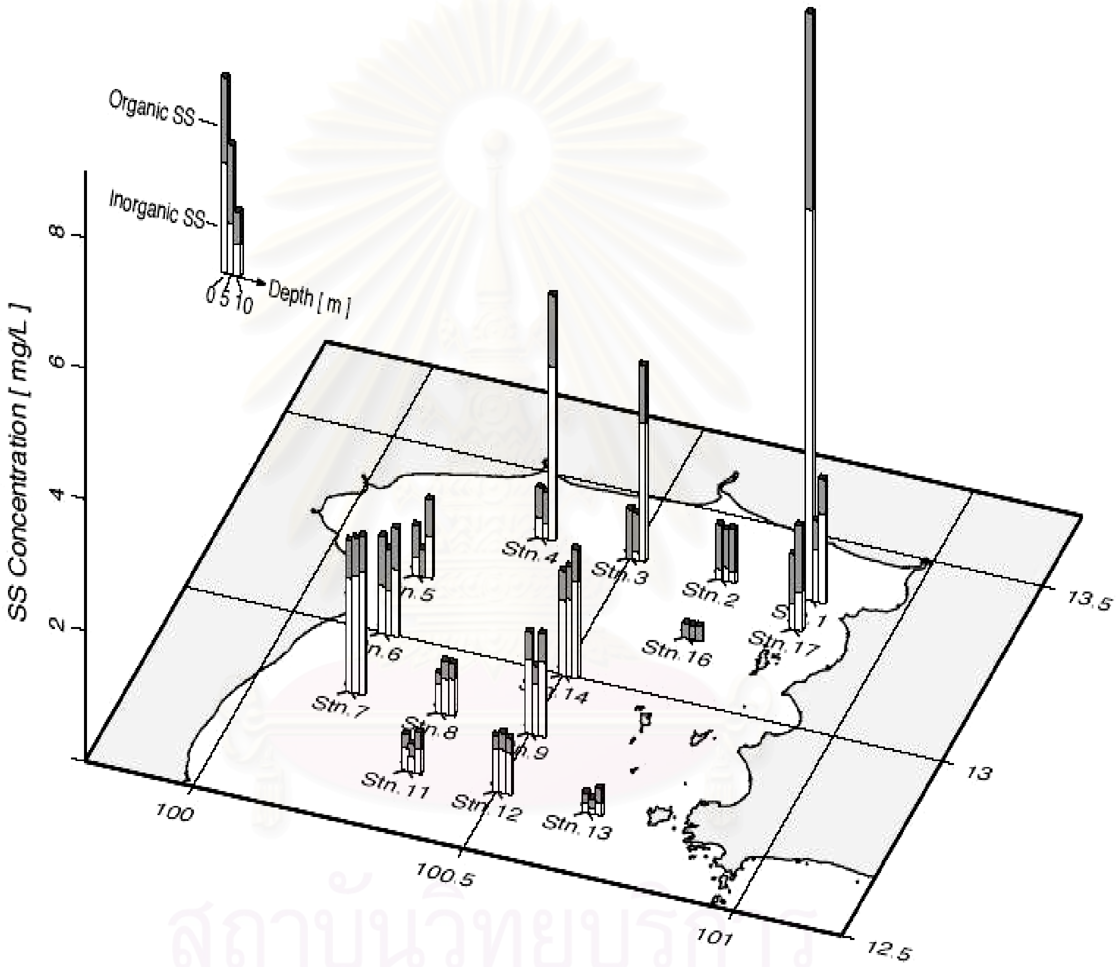

Figure E Proportions of organic and inorganic suspended sediments in the forth cruise survey during 12-15 May 2004 (Hiroshi Kobayashi, Yamanashi University, Japan)

BIOGRAPHY

Tachanat Bhatrasataponkul was born on 12 January 1981 in Bangkok. He received the Bachelor of Science in Marine Science with an area of concentration in Physical and Chemical Oceanography from Chulalongkorn University in 2002. After graduation, he further enrolled in the Master of Science Program in Marine Science with an area of concentration in Physical Oceanography at Chulalongkorn University.

With regard to his learning personality, he graduated with totally 260 credits divided into 176 credits in the Bachelor's degree and 64 credits in the Master's degrees. In addition to his academic profession, he received a teaching assistantship from Graduate School in the academic year 2002. Furthermore, he was granted a scholarship from Japan International Cooperation Agency (JICA) for short-term study visit in Japan concerning environmental technology and management during July to August 2004.

With respect to many youth activities, voluntary works and international affairs he has continually served throughout the years, he was honorarily awarded the National Outstanding Youth Award 2004 (Area of Youth Development and Public Affairs) from the Office of Welfare Promotion, Protection and Empowerment of Vulnerable Groups, Ministry of Social Development and Human Security.

In relation to this thesis, his article was accepted as an oral presentation at the 25th Asian Conference on Remote Sensing (ACRS 2004) (International Level), held during 22-26 November 2004 at Sheraton Chiangmai Hotel, Chiangmai, Thailand. Also, it was published in the Journal of Remote Sensing and GIS Association of Thailand.