RETRIEVAL OF ENVIRONMENTAL PARAMETERS OVER WATER AREAS USING MODIS DATA

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by

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LIST OF ABBREVIATION

ATSR-2	Along Track Scanning Radiometer 2
AATSR	Advanced Along Track Scanning Radiometer
AOD	Aerosol Optical Depth
APOLLO	Over cLouds Land and Ocean
AVHRR	Advanced Very High Resolution Radiometer
BTD	Brightness Temperature Difference
CALIOP	Cloud-Aerosol Lidar with Orthogonal Polarisation
CALIPSO	Cloud Aerosol Lidar and Infrared Pathfinder Satellite Observations
HIRS	High Resolution Infrared Radiation Sounder
IR	Infrared
L1B	Level 1B
MODIS	Moderate Resolution Imaging Spectroradiometer
MOD35	MODIS Terra cloud mask product
MYD35	MODIS Aqua cloud mask product
MOD04	MODIS Terra aerosol product
MYD04	MODIS Aqua aerosol product
MISR	Multiangle Imaging Spectro-Radiometer
NASA	National Aeronautics and Space Administration
nLw(λ)	Normalized water leaving radiance
NDVI	Normalized Difference Vegetation Index
NIR	Near Infrared
PM_{10}	Particulate Matter with diameter smaller than 10μm
$PM_{2.5}$	Particulate Matter with diameter smaller than 2.5μm
SeaWiFS	Sea-viewing Wide Field of view Sensor
SWIR	Short Wave Near Infrared
SSC	Suspended Sediment Concentration
UTC	Coordinated Universal Time

PENENTUAN PARAMETER PERSEKITARAN DI KAWASAN PERAIRAN MENGGUNAKAN DATA MODIS

ABSTRAK

Di dalam kajian ini, adalah dicadang dan ditunjukkan cara untuk mengenal pasti awan cirus, sedimen dan kedalaman optik aerosol (AOD) menggunakan data ‘Moderate Resolution Radiospectrometer’ (MODIS). Kaedah yang digunakan di dalam kajian ini merupakan penemuan terbaru di dalam bidang penderiaan jauh dan tidak pernah digunakan oleh mana-mana penyelidik sebelum ini. Kehadiran awan cirus dikenalpasti dengan menggunakan persamaan teknik kecerunan. Persamaan ini adalah berdasarkan kepada kecerunan garis yang menyambungkan saluran 1.38 dan 1.24 μm dari graf log-log pantulan ketara melawan panjang gelombang MODIS. Persamaan ini telah diuji ke atas kawasan Laut Kuning, Laut Mediterranean dan juga Lautan Atlantik. Keputusan persamaan ini telah dibandingkan dengan teknik nisbah saluran dan ketepatannya telah dikenalpasti dan peratus perbezaan dengan nisbah saluran kurang dari 10%.

Kehadiran pantulan oleh sedimen di dalam imej MODIS tidak hanya menyebabkan ketepuan di dalam saluran ‘Ocean Color’ tetapi juga meningkatkan pantulan di dalam saluran inframerah yang digunakan di dalam persamaan pembetulan atmosfera. Kesan ini menyebabkan terlebih anggaran bagi sumbangan oleh aerosol dan terkurang anggaran bagi penentuan pantulan yang meninggalkan air di dalam spektrum nampak. Kajian ini mencadangkan satu kaedah mudah untuk mengesan dan menopeng kawasan yang dilitupi sedimen di dalam data MODIS. Persamaan ini adalah berdasarkan kepada beza kecerunan bagi garis yang menyambungkan saluran 0.47 dan 2.13 μm dengan kecerunan garis yang menyambungkan saluran 0.47 dengan 0.66 μm dari graf log-log pantulan ketara

melawan panjang gelombang. Keputusan bagi kawasan kajian Laut Kuning, Teluk Martaban dan Laut Arab ditunjukkan. Ketepatan persamaan ini telah diuji dan disahkan. Perbandingan persamaan ini dengan persamaan yang telah kukuh memberikan persetujuan yang baik dengan peratus perbezaan kurang dari 10%.

Kajian tentang aerosol di dalam atmosfera merupakan elemen penting untuk memahami radiasi matahari yang masuk dan keluar dari bumi, keseimbangan kitaran air dan perubahan cuaca yang dinamik. Kajian ini mencadangkan satu persamaan mudah untuk menganggarkan AOD di atas permukaan air. Persamaan ini adalah berdasarkan kepada songsangan bagi kecerunan garis yang menyambungkan saluran 0.47, 1.24, 1.64 dan 2.13 μm bagi saluran atmosfera MODIS. Kesongsangan bagi kecerunan ini kemudiannya dibandingkan dengan peta AOD bagi saluran 0.869 μm yang diedarkan oleh pasukan 'Ocean Color' MODIS dengan menggunakan teknik regrasi. Keputusan dari teknik regrasi ini menunjukkan kesamaan yang baik dengan nilai $R>0.90$. Persamaan yang terhasil dari teknik ini kemudiannya digunakan untuk membina peta AOD bagi kawasan perairan.

RETRIEVAL OF ENVIRONMENTAL PARAMETERS OVER WATER AREAS USING MODIS DATA

ABSTRACT

In this study, new and simple algorithms to retrieve cirrus cloud, sediment and aerosol optical depth (AOD) from Moderate Resolution Radiospectrometer (MODIS) imagery is suggested and demonstrated. Techniques used in this thesis are totally new and never been used before by others researchers. The presences of cirrus cloud have been detected utilizing gradient technique algorithm. The algorithm is based on the gradient connecting the 1.38 and 1.24 μm lines of the log–log graph of apparent reflectance against the MODIS wavelength. This algorithm has been tested over the Yellow Sea, Gulf of Martaban, Mediterranean Sea and Atlantic Ocean. The result of this algorithm is then compared with the band ratio technique and the accuracy was determined with percentage difference below 10%.

The presence of sediment reflectance in the MODIS imagery not only saturate the ocean color channels, but also enhance the reflectance of near infrared channels used in the atmospheric correction algorithm. This leads to the overestimation of the aerosol contributions and underestimation of the derived water-leaving reflectance in the visible channels. In this study, a new and simple method to detect and mask the presence of sediment reflectance in the MODIS imagery is proposed. The algorithm is based on the difference of the gradient of the line connecting the 0.47 and 2.13 μm channels and 0.47 and 0.66 μm channels of a log–log graph of the apparent reflectance values against their MODIS wavelengths. A sample results over Yellow Sea, Gulf of Martaban and Arabian Sea was demonstrated. The accuracy of the algorithm was tested and determined. The comparison of this algorithm with the established algorithm also showed good agreement with percentage difference less than 10%.

The study of atmospheric aerosol is an important element to understand the earth's solar radiation budget, water cycle balance, and climate change dynamics. In this study, a new and simple algorithm to estimate the AOD over water region is proposed. The AOD retrieval algorithm is based on inverse gradient of the line connecting the channels of 0.47, 1.24, 1.64 and 2.13 μm of MODIS atmospheric channels. The gradient is then compared to the AOD map of 0.869 μm that is distributed by MODIS Ocean Color team using regression technique. The result of the regression shows good agreement with $R>0.90$. The resulted algorithm from this technique then used to construct the AOD over water region.

CHAPTER 1

INTRODUCTION

1.0 Introduction

Atmospheric aerosols, cirrus cloud and sediment reflectance play an important key role in the study of the Earth's climate system. Aerosols will influence the solar radiation both directly and indirectly through their various sizes and thus leads to their different optical and physical properties. When the aerosols are sufficiently large in size, they scatter and absorb sun light, and whereas these particles are small, they act as cloud condensation nuclei and aid in the formation of clouds (Rosenfeld, 2006). Although the dynamics modifies the aerosol size spectrum during their residence time, the particle population highly depends on the strength of their source and sinks mechanisms. As a consequence, concentrations of ambient aerosol will differ to a great extent between urban centers and remote areas, and between industrialized and rural regions (Rao et al., 2001). On a global scale, the natural sources of aerosols are more important than the anthropogenic aerosols, but regionally anthropogenic aerosols are more important (Ramanathan et al., 2001).

Apart from atmospheric aerosols, cirrus clouds are observed quite frequently, but they are one of the least understood components of the Earth's radiative budget. Previous studies have found that such clouds may influence the long-wave radiation budget near the tropical tropopause. It has been suggested that cirrus clouds could leads to the warming effect on the atmosphere whereas contrail cirrus can induce tropospheric warming over the world. Although the sediment is not directly influence the Earth's radiative budget, the presence of high sediment concentration in the remote sensing imagery can contributes to the systematic error in ocean and atmosphere products over coastal area around the world. At present, operational products over optically shallow waters are not produced.

The presence of remote sensing satellite makes it possible to collect data on dangerous or inaccessible areas and also replaces costly and slow data collection on the ground, hence ensuring that areas or objects are not disturbed. The quality of remote sensing data consists of its spatial, spectral, radiometric and temporal resolutions. There are numbers of remote sensing satellite that orbits the earth. Each satellite has their spatial, spectral and temporal resolution itself. The applications of the data are based on the research need.

1.1 Problem Statements

Currently Moderate Resolution Radiospectrometer (MODIS) team have distributed high quality land, ocean and atmosphere product. However, there are some uncertainties in the atmosphere and ocean products due to the contamination of cirrus cloud and sediment. Also, the algorithms that have been used to retrieve the environmental parameter such as aerosol, cirrus and chlorophyll are very complicated and needed high cost facilities to process. In this section, problem statement will be defined and the motivation in conducting this research will be discussed.

This section is organized as follows. Firstly, the statement of the problems which relates to the retrieval of cirrus clouds over water will be discussed thoroughly. Following that is the discussion of problem statement which relates to sediment. Finally, at the last part, is the discussion of problems statement which relates to the retrieval of aerosol optical depth (AOD).

1.1.1 Cirrus Clouds

Numerous studies have been conducted to retrieve the presence of cirrus cloud over ocean region (Roskovensky & Liou, 2006). MODIS cloud mask product (MOD35/MYD35) has used two cirrus cloud mask algorithm. The first algorithm is based on the brightness temperature difference (BTD) of MODIS channels 3.9 and 12 µm channels. The second algorithm is based on the reflectance of 1.38 µm channels (Ackerman et al., 2010). Both of the algorithms are based on the threshold. Until now, the threshold used in the product has been reviewed several times (Ackerman et al., 2010). Due to the difficulty to distinguish the cirrus cloud from trophosperic aerosol over ocean region, Gao et al., (2002) have proposed a band ratio technique to discriminate cirrus cloud from MODIS imagery. The algorithms have successfully removed the presence of cirrus cloud over ocean and the algorithm is currently applied by the MODIS aerosol team as an added algorithm to discriminate cirrus and tropospheric aerosol over ocean region. Other researcher, Roskovensky & Liou (2003) have proposed a band ratio of 1.38 µm/0.65 µm with combination with temperature difference of 8.6-11 µm channels. The algorithm was able to detect the majority of thin cirrus that has optical depth between 0.1 and 0.9.

Although there are numbers of cirrus clouds masking algorithms proposed by many researchers, still exist the contamination of the cloud and contribute to the increment in the AOD retrieve by the MODIS aerosol team (Kaufman et al., 2005). This is due to the existence of the residual cloud in the image after the cloud masking process. In this research, a new and simple algorithm that is based on the gradient line that connecting the 1.38 and 1.24 µm lines of the log–log graph of apparent reflectance against the MODIS wavelength is proposed. The algorithm is tested over the numbers of geographical region and the accuracy is determined.

1.1.2 Sediment

The atmospheric correction algorithm for MODIS uses aerosol information derived from sensor-measured two near-infrared (NIR) bands and then extrapolates it into visible wavelengths through evaluation of the aerosol parameter (Gordon & Wang, 1994; Wang & Shi, 2005). In this algorithm, the oceans at the two NIR bands (748 and 869 nm for MODIS) are assumed to be black in order to effect the atmospheric correction and derive aerosol properties. However, the turbid waters could have significant contributions at the NIR bands, leading to an overestimation of aerosol contributions and an underestimation of the derived water-leaving reflectance in the visible (Wang & Shi, 2005). The ocean color images, as routinely processed by several space agencies, often shows red color (a color encoding attributed to very high chlorophyll concentration) along many coasts of the world ocean and particularly in semienclosed seas (Morel & Belanger, 2006).

Even if there are good reasons to expect from the sizeable enhancements of the algal biomass in these shallow zones (because of a possible nutrient influx from terrestrial origin, and/or rapid recycling of nutrients), it is also known that the algorithms (of the blue-to-green ratio type) developed for open ocean waters fail in such zones, with the result of strongly overestimating chlorophyll (Morel & Belanger, 2006; Morel & Prieur, 1997). Due to this uncertainty, turbid area along coastal (Case 2) waters needs to be clearly distinguished from open ocean region (Case 1) waters.

In order to overcome this problem, the effect of sediment or inorganic suspended matter in the signal measured by satellite sensor should be discarded from the image. Li et al. (2003) have proposed a method that is based on the power law algorithm. An increment in the 0.55 μm channels over the power law line is assumed contributed by the sediment reflectance and the pixels is then masked as sediment-influence pixels. This algorithm currently used by the MODIS aerosol team to masked the presence of sediment reflectance in the MODIS imagery. This algorithm is known too complicated and difficult. In this study a simple method to remove the sediment reflectance from MODIS imagery over bright coastal waters for MODIS visible and near infrared channels is proposed.

1.1.3 Aerosol Optical Depth (AOD)

In order to generate high-end ocean and land product, the AOD retrieved must be in the highest quality. Currently, MODIS aerosol team have distribute AOD map over ocean and land region. The pixels size for the product is degraded into 10 km x 10 km. The algorithm used to retrieve the AOD over ocean is based on 'look-up table' approach. In this approach, radiative transfer calculations are pre-computed for a set of aerosol and surface parameters and then compared with the observed radiation field. The algorithm used to retrieve the AOD is known to be sophisticated and complicated to reprocess manually.

In order to implement a simple and accurate algorithm, a new technique has been developed to retrieve the AOD over ocean region. This new technique is based on the inverse gradient of the line connecting the 0.47, 1.24, 1.64 and 2.3 μm channels. Even though this algorithm is new and simple it is also known to be in high correlation with AOD map distributed by the MODIS Ocean Color team.

1.2 Research Scope and Objectives

This section is organized as follows. First is the discussion about the scope of the research followed by the objectives of the research.

1.2.1 Research Scope

Two types of MODIS datasets are used in this study, namely L1B calibrated radiances data (MOD02) and Ocean Color Product. This study is only conducted over water area. The main study areas are Gulf of Martaban which is located between Myanmar and Thailand, and Yellow Sea which is located between China and Korea. In order to construct a simple algorithm without compromising its accuracy, an empirical technique has been used. The results of the new algorithms are compared to the other established algorithms to ensure the accuracy of the algorithm.

1.2.2 Research Objectives

The main objectives of this thesis are described as follow. The objectives are to develop a new and simple algorithm utilizing MODIS L1B data to;

a) detect and mask the presence of cirrus cloud over water area.

b) detect and mask the pixels influenced by sediment reflectance in the MODIS imagery.

c) estimate the AOD over water area.

1.3 Research Outline

The flowchart of the overall processing step is shown in Figure 1.1. The first step is the ocean test. This test was conducted in order to retrieve the environmental parameter over water area.

The second step is cloud test. This test is conducted to distinguish cloudy and clear scene over the study area. In this test, MODIS cloud mask algorithm over water is used. Regional threshold have been used to mask the pixels influence by the cloud. Another test called cirrus cloud test that is based on the gradient technique have been added in this masking scheme. Pixels that are detected to be influence by cirrus cloud are then masked. The processing steps are continued if the pixels are detected as cloud free pixels.

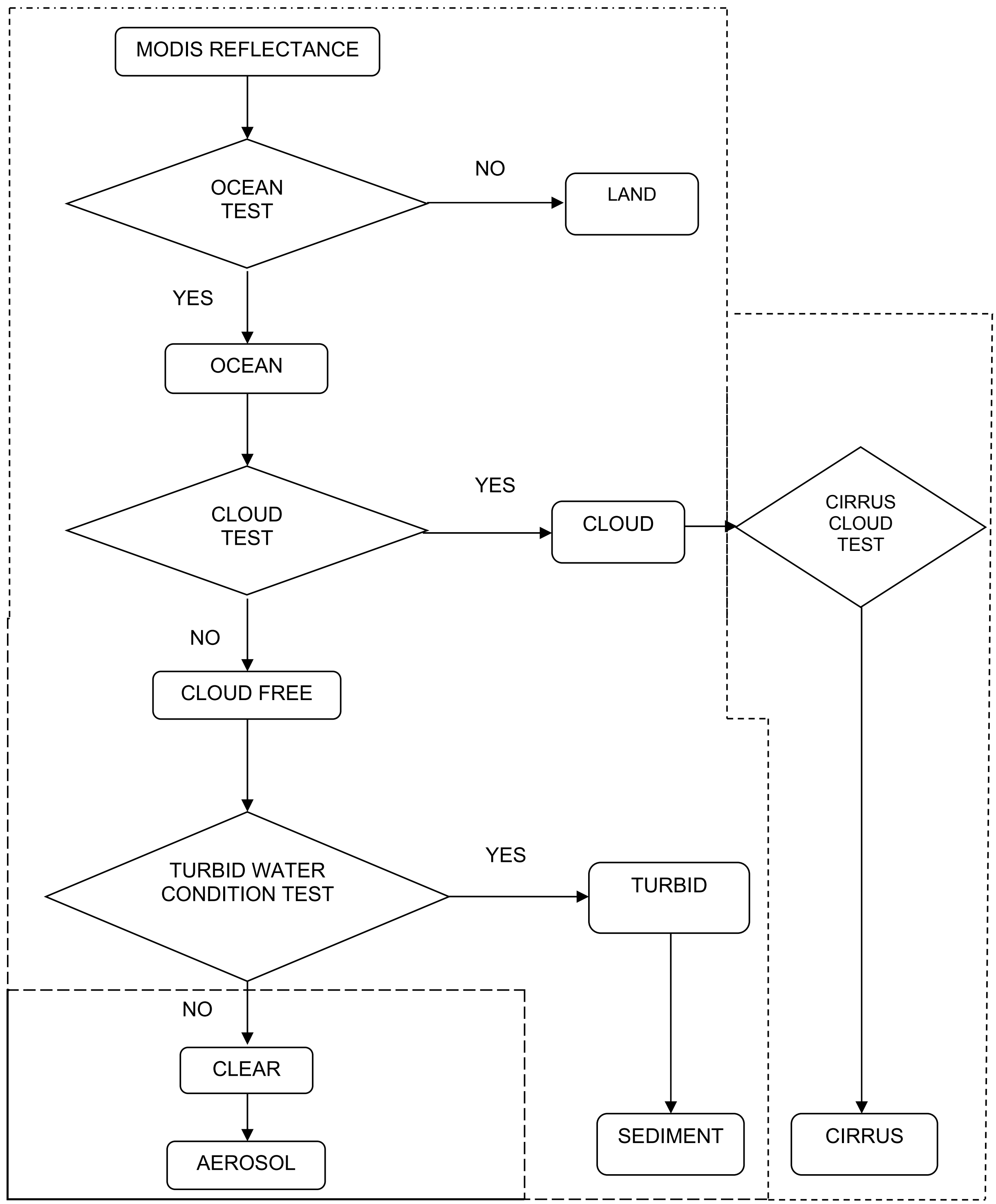

Figure 1.1: Overall flowchart of the study. The processing steps involving three main parts: cirrus cloud masking, sediment masking and retrieval of aerosol optical depth retrieval.

The third step is turbid water condition test. This test is conducted to the pixels that are not detected as cloud by the cloud test algorithm. This test is implemented to discriminate the clear and sediment influence pixels over water region. These two areas were discriminated using the simple sediment discriminating algorithm. The algorithm is based on the gradient difference over the study area. Pixels that are detected to be influence by sediment reflectance are then masked.

The fourth and the last processing step are to estimate the AOD over ocean region using a new technique. This technique is conducted over the pixels that were indicated as water by the water condition test. The gradient line of log-log graph of apparent reflectance against wavelength shows high correlation with the aerosol contribution. The gradient line is then compared to the AOD map distributed by the MODIS Ocean Color team using regression technique. The AOD map is then constructed using the algorithm obtained by the regression technique.

1.4 Thesis Organization

This thesis is divided into seven chapters. The details methodologies of the study are discussed in the respective chapter.

Chapter 1 contains the motivation of this research work and introduction to this thesis. It explains the problem statements, research scope and the objectives of the study. The flowchart and the outline of the thesis organization are also provided in this chapter for ease of understanding.

Chapter 2 discusses about the literature review of this study. This chapter is organized as follow. First, is the discussion about the literature review of the land and cloud masking scheme that commonly used in each study. Secondly is the discussion about the literature review of cirrus retrieval over water area. After that, the discussion about the literature review of the sediment retrieval over water area is presented. Finally, the literature review of AOD retrieval water area is discussed.

Chapter 3 discusses about the materials and methodology used in this study. The discussion starts with the introduction to the instrument used in this study. After that, the data used in this study is provided and discussed. The discussion about the study area areas also presented in this chapter. Following that is the discussion about the methodology of the study. The discussion starts with the methodology of land and cloud masking that are commonly used in every study. Later on, a brief discussion about the methodology of cirrus cloud retrieval over ocean is presented followed by the brief discussion of the methodology to retrieve sediment influence area. Finally is the brief discussion about the methodology to retrieve AOD over water area is presented. The detail discussion about cirrus cloud retrieval, sediment retrieval and AOD retrieval are discussed in Chapter 4, Chapter 5 and Chapter 6 respectively.

Chapter 4 described in detail the construction of an algorithm to detect the presence of cirrus cloud over water area. This chapter begins with the introduction of this study. This section also discussed about the development of the algorithm and the technique used to obtain the algorithm threshold. The result and discussion are also presented. The last section is the summary for the chapter.

Chapter 5 described the development of algorithm to detect the presence of sediment reflectance in the MODIS imagery. In the methodology section, a technique to develop the algorithm and to obtain the algorithm threshold is also discussed. The result and discussion is presented and explained. The last section is also the summary for the chapter.

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Chapter 6 described about the method to estimate AOD over water area. This chapter begins with the methodology of the study. The discussion about the technique used, also are discussed in this section. Detailed analysis about the result of the study is discussed thoroughly. Final section of this chapter concludes the summary.

Chapter 7 concluded this thesis by providing a summary of the work. This chapter also discussed the contributions of the research work and the future directions that can be further taken from this work.

CHAPTER 2

LITERATURE REVIEW

2.0 Introduction

This thesis presents studies which were conducted to retrieve three environmental parameters over water area. In this chapter, the literature reviews for each objective of the thesis are presented. This chapter is organized as follows. Firstly, in order to study the water and atmospheric parameters, the presence of land and cloud in the MODIS image should be masked. Then, the literature reviews of this masking scheme are discussed in section 2.1. After that, the literature review for the cirrus cloud retrieval over water area is discussed in section 2.2. Following that, section 2.3 provides the literature review for the sediment. Finally, the literature review for AOD is presented in section 2.4

2.1 Land and cloud masking

Cloud plays an important role in the earth energy budget calculation. They provide good shield from infrared radiation, reflects the visible solar back into space and also causes a greenhouse effect by trapping infrared radiation in the atmosphere. However the presence of cloud in the atmosphere can cause problems for remote sensing community to detect clear view of earth because of their obstruction properties. The cloud shadow also reduce the incoming and reflected light. Most of the remote sensing algorithms used to measure biological and physical properties of the atmosphere over earth needed a cloud free scene. So, it is important to determine the cloud properties and their distribution in the atmosphere before it can be masked. There are numbers of cloud detection methods used such as comparison of two wavelengths, infrared variability and using two infrared-visible methods.

MODIS cloud mask uses multispectral imagery to indicate whether the scene is clear, cloudy, or affected by shadows (Ackerman, 1997). The mask is generated at 250 m and 1 km resolutions, day and night. A comprehensive set of remote sensing algorithms for cloud detection and the retrieval of cloud physical and optical properties have been developed by members of the MODIS atmosphere science team (Platnick et al., 2003).The MODIS cloud mask product is based on the principles of Advanced Very High Radiometer (AVHHR) processing scheme Over Clouds Land and Ocean (APOLLO) cloud mask algorithm, but it makes use of the additional spectral information available from the 36 channels collected by the MODIS sensor (Ackerman et al., 1998; 2010). MODIS algorithm is based on applying a number of spectral threshold tests to the reflectance values for each pixel. The tests applied to the data are designed to identify cloud detected at different wavelengths. 17/36 spectral bands ranging from 0.55-13.93 μm have been used. Eleven different spectral tests are performed, with different tests being conducted over each of 5 differerent domains (land, ocean, coast, snow, and desert). Algorithm is based on radiance thresholds in the infrared, and reflectance and reflectance ratio thresholds in the visible and near-infrared. A more detailed discussion of the MODIS cloud mask algorithm is represented in Ackerman et al. (1997; 1998; 2010).

In order to discriminate cloud and aerosol over water, the use of spectral test alone are problematic (Ackerman et al., 2010). The spectral test may flag the heavy aerosol-laden as cloud. Because of that, MODIS aerosol team has developed a different cloud mask algorithm to discriminate cloud and troposperic aerosol over water region (Levy et al., 2009). The MODIS aerosol team has added spatial variability test (Martins et. al., 2002) and band ratio technique (Gao et al., 2002) in their cloud mask algorithm scheme over water area. The algorithms are known too complicated to be applied.

The next following sub-chapter is the review of researched development in Cirrus Cloud, sediment and AOD retrieval over water which are related to Chapter 4, Chapter 5 and Chapter 6.

2.2 Cirrus Cloud

Cirrus cloud is the one over ten types of cloud genus. Cirrus clouds form at the highest and coldest region of the troposphere. The cirrus clouds have been observed at all latitudes (McFarquhar et al., 2000; Sassen & Cho, 1992) and occur on large horizontal scales and are relatively long lived (Liou, 1986). Thin cirrus coverage is also widespread, especially in the Tropics. Wylie & Menzel (1999) illustrated, by analyzing 8 years of data, that semitransparent cirrus occured in 43% of the High Resolution Infrared Radiation Sounder (HIRS) observations. During the boreal summer, they found out that the effective cloud fraction of cloud that is higher than 6 km was greater than 80% over Southeast Asia and the western equatorial Pacific.

Aerosols and ice particles in cirrus both affect the radiation fluxes and vertical temperature structure of the atmosphere by interacting with radiation from the sun and the earth–atmosphere system. Tropospheric aerosols absorb and reflect the incoming solar radiation, which generally leads to a cooling of the surface by reducing the net downward solar flux. Chou et al. (2002) analyzed data from the Sea-viewing Wide Field-of view Sensor (SeaWiFS) and obtained values of 5.9 and 5.4 W m^{-2} for the aerosol induced reduction in solar flux at the surface and at the top of the atmosphere, respectively. Because of their small sizes (~1 μm), tropospheric aerosols affect the thermal infrared radiation field only in a minor way compared to that of their influence on solar radiation (Ackerman, 1997). However, small ice crystals in thin cirrus absorb infrared energy efficiently, especially in the shorter wavelength region of the infrared window (Smith et al. 1998).

The MODIS cloud mask uses 19 visible and IR regions out of 36 channels of MODIS L1B radiance data as inputs into the cloud mask algorithm (Ackerman et al., 1998). The measurement of the biological and physical properties over Earth needs a cloud-free scene. The contamination of remote sensing data by clouds remains a major problem and is a leading source of error when retrieving aerosol and surface properties from satellites (Mischenko et al., 1999). Therefore, a clear atmosphere has to be first determined. The MODIS cloud mask uses multispectral imagery to indicate whether the scene is clear, cloudy or affected by shadows (Ackerman, 1997), and thereby acts an as input for atmosphere, land and ocean algorithms. The mask is generated at 250 m and 1 km resolutions, day and night. The MODIS algorithm is based on applying a number of spectral threshold tests to the reflectance values for each pixel. The tests applied to the data are designed to identify clouds detected at different wavelengths.

The presence of thin cirrus clouds in remote sensing data is traditionally difficult to detect in visible and IR atmospheric window regions due to the clouds that is partially transparent in atmospheric window channels (Gao & Li, 2008). A reflectance at 1.38 μm, which is effective in detecting upper level cirrus cloud, has been used to improve the detection of thin cirrus clouds (Gao et al., 1993; Gao & Kaufman, 1995). In this channel, high clouds appear brighter because of relatively low specific humidity.

MODIS aerosol team have used spatial variability test over ocean (Martins at al., 2002) supported by cirrus test using the 1.38 μm channel and few remaining MODIS cloud mask product in the ocean algorithm to discriminate cloud (Levy et al., 2009). Cirrus clouds over the ocean in the MODIS aerosol product (MOD04/MYD04) algorithm are identified with a combination of infrared (IR) and near IR red tests. The IR tests provided by MODIS cloud mask are IR cirrus test, 6.7 μm tests and infrared difference test (Levy et al., 2009). The additional cirrus detection algorithms utilizing 1.38 μm channel and band ratio technique (Gao et al., 2002) produced very successful cloud masking results where tropospheric aerosol and thin cirrus cloud pixels were successfully distinguished. The band ratio equation is defined as follow:

$$\text{Band ratio} = \frac{\rho_{1.38}\ \mu\text{m}}{\rho_{1.24}\ \mu\text{m}} \tag{2.1}$$

Whereas $\rho_{1.38}$ and $\rho_{1.24}$ denotes the reflectance of 1.38 and 1.24 μm channels respectively.

2.3 Sediment

The atmospheric correction algorithm for MODIS uses aerosol information derived from sensor-measured two NIR bands and then extrapolates it into visible wavelengths through evaluation of the aerosol parameter (Yu et al., 2006; Levy et al., 2007). The ocean at the two NIR bands (748 and 869 nm for MODIS) is usually assumed to be black in order to effect the atmospheric correction and derive aerosol properties. However, for the turbid ocean waters, ocean could have significant contributions at the NIR bands, leading to an overestimation of aerosol contributions and an underestimation of the derived water-leaving reflectance in the visible channels (Wang & Shi, 2005). The ocean color images, as routinely processed by several space agencies, often show red color (a color encoding attributed to very high chlorophyll concentration) along many coasts of the world ocean and particularly in semi-enclosed seas (Morel & Belanger, 2006).

The fact that the suspended sediments increase the radiant emergent from surface waters in the visible and near infrared region of the electromagnet spectrum has been made since late 1970’s (Ritchie et al., 1976). Most researches that had a large range (i.e., 0-200 mg l^{-1}) of suspended sediment concentration have found a curvilinear relationship between suspended sediments and radiance or reflectance

(Ritchie et al., 1976; 1990; Curran et al., 1988). This is because the amount of reflected radiance tends to saturate the respected channels used for detection as suspended sediment concentrations increase. The point of saturation is wavelength dependent, with the shorter wavelength channels saturating at lower concentrations (Ritchie & Cooper, 1988).

Numerous investigators have established relationship between reflected solar radiance measured by remote sensing instruments with suspended sediments in a wide range of inland and coastal waters. Li et al. (2003) have developed an algorithm to detect sediment dominated water using MODIS measurements at the short wave infrared (SWIR) and green channel. The contributions of the sediment are indicated by the increments in the reflectance of the green channel above the power law line. While Morel and Belanger (2006) have refined the scheme using normalized water leaving radiance (nLw(λ)) threshold value at the green band for the turbid water detection. Wang & Shi (2005) use the combinations of the MODIS measured radiances at the short visible, NIR, and short wave infrared (SWIR) bands. Another method was developed by Figueras et al. (2004) by using a null point at 497nm (corresponding to SeaWiFS band 4 centered at 510 nm) where the level of reflectance is not affected by change in chlorophyll concentration.

2.4 Aerosol Optical Depth

The aerosols are produced mainly by the mechanical disintegration processes occurring over land and oceanic regions and by chemical reactions occurring in the atmosphere. Aerosol particles play important roles in climate system of the earth and the hydrological cycle. They also influence the Earth's radiation balance by scattering and absorbing solar radiation and are also harmful to human health. Toxic heavy metals, acid oxide, and organic pollutants borne in PM_{10}, $PM_{2.5}$ of aerosol total suspended particles can infect human lungs easily (Wang et al., 2010). Finally, aerosol particles make air cloud and blur remote sensing images. Many studies revealed that PM_{10} and $PM_{2.5}$ can reduce the visibility of air (Appel et al., 1985, Wang et al., 2010) and change apparent reflectance of satellite as a part of path radiance. Therefore, effective information of aerosol retrieval is also essential to satellite imagery atmospheric correction.

Aerosol optical depth (AOD) represents the attenuation rate of solar radiant energy passing through aerosphere. It is an important physical quantity of atmospheric turbidity and a key factor of aerosol climatic effects. Currently, two approaches are adopted to derive AOD: ground-based detection and remote sensing retrieval. The former could derive detailed AOD and its properties using sun spectrophotometer, but only acquires point data in space. The latter can provide the spatial and temporal resolution to measure the inhomogeneous aerosol fields. To date, remote sensing of aerosol over homogeneous surface, like ocean, using satellite data has been used in large quantity. However, over heterogeneous land surface, like desert, it has been not mature enough yet (Wang et al., 2010).

Until recently, there has been a long history of the quantitative estimation of AOD from remotely sensed imagery. As the successive launches of remote sensors, many algorithms have been proposed and applied to retrieve AOD using satellite datasets, for instance, using multi-angular information (Diner et al., 2005), polarization information (Deuze et al., 2001) and multi-spectral information (Kaufman et al., 1997). Multi-angle imaging radiometers offer the potential to improve the separation of scattering and absorption attenuation caused by the atmosphere from the scattering at the land surface (North et al., 1999; 2002). With the launch of the Along Track Scanning Radiometer 2 (ATSR-2) (Flowerdew and Haight, 1995; Veefkind et al., 1998) and the Advanced Along Track Scanning Radiometer (AATSR) (Grey et al., 2006), the retrieval of AOD using multi-angle imaging were widely considered to be successful. Besides, the Multiangle Imaging Spectro-Radiometer (MISR) sensor (Diner et al., 2001; Kahn et al., 2001) is being used, too. The MODIS science team (Remer et al., 2005) uses the dark-object method to estimate aerosol optical depth from MODIS imagery over land for climate study (Liang et al., 2006).

The MODIS aerosol algorithm is actually two entirely independent algorithms, one for deriving aerosols over land and the second for aerosols over ocean. Both algorithms were conceived and developed before the Terra launch and are described in depth in Kaufman et al. (1997) and Tanré et al. (1997). This document also known as the 1996_MOD04 Algorithm Theoretical Basis Document (ATBD-96). The AOD over water algorithm is based on a 'look-up table' (LUT) approach. In this approach, radiative transfer calculations are pre-computed for a set of aerosol and surface parameters and compared with the observed radiation field. The algorithm assumes that one fine and one coarse lognormal aerosol modes can be combined with proper weightings to represent the ambient aerosol properties over the target. Spectral reflectance from the LUT is compared with MODIS-measured spectral reflectance to find the 'best' (least-squares) fit. This best fit or an 'average' of a set of the best fits is the solution to the inversion.

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CHAPTER 3

MATERIAL AND METHODOLOGY

3.0 Introduction

This study is conducted over water area in order to retrieve three main objectives as mentioned in the previous chapter. Although there are three objectives in this study, the type of instrument and data used in each objective are the same. However, the common processing used in each study involves the application of land and cloud masking algorithms. In this chapter, the discussion of the materials and methodology of the study conducted is presented. The discussion of the instrument used in this study is mentioned in section 3.1. The characteristics of the instrument, the product distributed and the data used in this study are also discussed in this section. Following that, in section 3.2 the discussion of the study areas is presented. Finally, section 3.3 briefly discusses the methodology of each objective as mentioned in Chapter 1. The detailed discussions are presented in their respective chapter (Chapter 4, Chapter 5 and Chapter 6).

3.1 Research Instrument

In this study, Moderate Resolution Imaging Spectroradiometer (MODIS) with high temporal resolution is used. High temporal provide the continuation in the data collection. This section will discuss about the instrument used in this study. The discussion started with the characteristics of the instrument. After that the discussion about the product distributed by MODIS will be provided.

3.1.1 MODIS Characteristics

Imaging spectrometry has an important application in large variety of fields, including mineral explorations, vegetation studies, and coastal monitoring. Since the mid 1980’s, the concepts of imaging spectrometry and hyperspectral imaging have become increasingly popular. MODIS was launched aboard Terra satellite in late 1999 and aboard Aqua satellite in early 2002. Both satellites are polar-orbiting, with Terra on a descending orbit (southward) over the equator about 10:30 local sun time, and Aqua on an ascending orbit (northward) over the equator about 13:30 local sun time. MODIS will view the entire surface of the Earth every 1-2 days.

From a vantage of about 700 km above the surface and a ±55° view scan, each MODIS views the earth with a swath about 2330 km, thereby observing nearly the entire globe on a daily basis, and repeat orbits in every 16 days. MODIS performs measurements in the visible to thermal infrared spectral region from 0.41 to 14.235 μm (Salomonson et al., 1989). MODIS data have been used to answer scientific questions about radiation and climate (Yu et al., 2006; Levy et al., 2007). The MODIS instruments measure spectral radiance in 36 channels, in resolutions between 250 m and 1 km (at nadir). MODIS instrument was designed to support observation of clouds and land as well as oceans. Table 3.1 shows the characteristics of the MODIS channels (https://lpdaac.usgs.gov/lpdaac/products/modis_overview).

Table 3.1: MODIS spectral band

BAND	**RANGE nm**	**RANGE μm**	**KEY USE**
	Reflected	Emitted	
1	620–670		Absolute Land Cover Transformation, Vegetation Chlorophyll
2	841–876		Cloud Amount, Vegetation Land Cover Transformation
3	459–479		Soil/Vegetation Differences
4	545–565		Green Vegetation
5	1230–1250		Leaf/Canopy Differences
6	1628–1652		Snow/Cloud Differences
7	2105–2155		Cloud Properties, Land Properties
8	405–420		Chlorophyll

Table 3.1: MODIS spectral band (continued)

9	438–448		Chlorophyll
10	483–493		Chlorophyll
11	526–536		Chlorophyll
12	546–556		Sediments
13h	662–672		Atmosphere, Sediments
13l	662–672		Atmosphere, Sediments
14h	673–683		Chlorophyll Fluorescence
14l	673–683		Chlorophyll Fluorescence
15	743–753		Aerosol Properties
16	862–877		Aerosol Properties, Atmospheric Properties
17	890–920		Atmospheric Properties, Cloud Properties
18	931–941		Atmospheric Properties, Cloud Properties
19	915–965		Atmospheric Properties, Cloud Properties
20		3.660–3.840	Sea Surface Temperature
21		3.929–3.989	Forest Fires & Volcanoes
22		3.929–3.989	Cloud Temperature, Surface Temperature
23		4.020–4.080	Cloud Temperature, Surface Temperature
24		4.433–4.498	Cloud Fraction, Troposphere Temperature
25		4.482–4.549	Cloud Fraction, Troposphere Temperature
26	1360–1390		Cloud Fraction (Thin Cirrus), Troposphere Temperature
27		6.535–6.895	Mid Troposphere Humidity
28		7.175–7.475	Upper Troposphere Humidity
29		8.400–8.700	Surface Temperature
30		9.580–9.880	Total Ozone
31		10.780–11.280	Cloud Temperature, Forest Fires & Volcanoes, Surface Temp.
32		11.770–12.270	Cloud Height, Forest Fires & Volcanoes, Surface Temperature
33		13.185–13.485	Cloud Fraction, Cloud Height
34		13.485–13.785	Cloud Fraction, Cloud Height
35		13.785–14.085	Cloud Fraction, Cloud Height
36		14.085–14.385	Cloud Fraction, Cloud Height

3.1.2 MODIS Products

The MODIS instrument calibration, algorithm development, and standard data products are provided by the MODIS science team. There are four science team groups: calibration, land, atmosphere, and ocean. Each group has clearly defined scientific responsibilities, and close interactions between the groups are maintained throughout the algorithm development, data processing, evaluation and product distribution.

There are five categories of MODIS product known as level 0 to level 4. Level 0 data is the initial dataset that is automatically converted from raw instrument format. The level 0 data is subsequently split into different granules and an earth location algorithm is employed to add geodetic position information to each of this MODIS granule. This creates the MODIS level 1A product that contains geodetic information such as latitude, longitude, height, satellite zenith/azimuth and solar zenith/azimuth angles. The level 1A data is further processed to generate level 1B product (calibrated radiance for all bands and surface reflectance values for selected bands). Additional information such as data quality flags and error estimates are also provided. Level 3 data provides an estimation of optical or biophysical variables for each grid element for predefined spatial and temporal resolutions (e.g., daily, eight-day, and monthly). Finally, level-4 data is generated through a variety of algorithms, models, and statistical methods. MODIS data products are also labeled by collection version. Each collection version indicates a complete set of MODIS files corresponding to a specific data updating or re-processing stage. In this study, MODIS level 1B product was used.

3.1.3 MODIS Data

In this study, data acquired over Yellow Sea and Gulf of Martaban and nearby area have been used as main study area. However, data from another area were also used in this study in order to test the algorithm from different geographical areas. The data have been downloaded from MODIS atmosphere (http://ladsweb.nascom.nasa.gov) and ocean color website (http://oceancolor.gsfc.nasa.gov/seadas). Images used in this study were selected to ensure that all the parameters needed in the study are available in the image.

Table 3.2: Data for the study area

No.	Location	Data	Chapter		
1	Yellow Sea	MOD021KM.A2008093.0320.005.2010235004704.hdf	4	5	
2		MOD021KM.A2008094.0225.005.2010235012039.hdf	4	5	
3		MOD021KM.A2008096.0215.005.2010235021322.hdf	4	5	
4		MOD021KM.A2008135.0220.005.2010237163945.hdf	4	5	
5		MOD021KM.A2008140.0240.005.2010237215207.hdf	4	5	
6		MOD021KM.A2008163.0245.005.2010239132640.hdf	4	5	
7		MOD021KM.A2008188.0240.005.2010243145705.hdf	4	5	
8		MOD021KM.A2008250.0250.005.2010249174247.hdf	4	5	
9		MOD021KM.A2008252.0240.005.2010249221509.hdf	4	5	
10		MOD021KM.A2008256.0215.005.2010249225404.hdf	4	5	
11		MOD021KM.A2009283.0210.005.2010252222204.hdf	4	5	
12		MOD021KM.A2009293.0245.005.2010253123306.hdf	4	5	
13		MOD021KM.A2009297.0220.005.2010253184843.hdf	4	5	
14		MOD021KM.A2009309.0245.005.2010254065247.hdf	4	5	
15		MOD021KM.A2001079.0255.005.2010060230504.hdf	4	5	6
16	Gulf of Martaban	MOD021KM.A2008007.0405.005.2010212000457.hdf	4	5	
17		MOD021KM.A2008316.0425.005.2010110023722.hdf	4	5	
18		MOD021KM.A2008318.0410.005.2010106201847.hdf	4	5	
19		MOD021KM.A2008320.0400.005.2010106201759.hdf	4	5	6
20		MOD021KM.A2008323.0430.005.2010110022240.hdf	4	5	6
21		MOD021KM.A2008327.0405.005.2010106201431.hdf	4	5	6
22		MOD021KM.A2008332.0425.005.2010106201742.hdf	4	5	6
23		MOD021KM.A2008334.0410.005.2010106201908.hdf	4	5	6
24		MOD021KM.A2009002.0400.005.2010233184514.hdf	4	5	
25		MOD021KM.A2009005.0430.005.2010234003406.hdf	4	5	
26		MOD021KM.A2009009.0405.005.2010234041953.hdf	4	5	
27		MOD021KM.A2009092.0435.005.2010239113321.hdf	4	5	
28		MOD021KM.A2009307.0440.005.2010254050648.hdf	4	5	
29		MOD021KM.A2009313.0405.005.2010254223703.hdf	4	5	
30		MOD021KM.A2009316.0435.005.2010255010559.hdf	4	5	
31	Arabian Sea	MOD021KM.A2001301.0625.005.2010074045243.hdf	4	5	
32	Mediterranean Sea	MOD021KM.A2004087.1015.005.2010135185313.hdf	4		
33	Atlantic Ocean	MOD021KM.A2010024.1440.005.2010259180622.hdf	4		
34	Gulf of Martaban (Ocean Color)	T2008320040000.L2_LAC			6
35		T2008323043000.L2_LAC			6
36		T2008327040500.L2_LAC			6
37		T2008332042500.L2_LAC			6
38		T2008334041000.L2_LAC			6

Though, not every images distributed by the MODIS can be analyzed. This is because the images are highly contaminated by clouds or the images are not geographically completed. Not all images were used in every chapter. For an example, ocean color images that consist of AOD map for 0.867 μm channel is only used in Chapter 5. In this section, the data taken for the study location is listed as shown in Table 3.2. All of the images downloaded are tested to ensure the accuracy of the algorithm constructed. However, in this study, only certain images were selected to be the example for each of the algorithm. Based on statistical method, it is believed that these small numbers of images are considered enough to represent the large number of images used.

In this study, 15 MODIS L1B data acquired over the Yellow Sea and 15 data acquired over the Gulf of Martaban have been used. All of the data from these two areas have been used in all chapters. A data acquired over the Arabian Sea are used in the Chapter 4 and 5. Data for Mediterranean Sea and the Atlantic Ocean are used in the Chapter 4 only. Finally, the last data that is Ocean Color level 2 products acquired over the Gulf of Martaban are used in the Chapter 6.

3.2 Study Areas

The main objective of this study is to develop a new and simple algorithm that could be used globally. A numbers of region over the world, including Malaysia had been selected to be used as the study area. However, at some point of the research, it was found out that the MODIS pixel size that is used in this study are too large to be applied over Malaysian coastal water. Therefore, Malaysian area has been ruled out or not to be selected for this study. Finally, two areas have been selected which is believed can give the best possible finding for this study. The two areas that have been chosen as the main study area are;

a) Gulf of Martaban and nearby area (located between Thailand and Myanmar)
b) Yellow Sea and nearby area (located between China and Korea)

These two areas are recognized as the most influence by sediment due to the presence of a number of river flows to that area. Number of study have also been conducted over these are by other researchers such as Li et al., (2003), Gao et al., (2002), Ramaswamy et al., (2004) and Liu et al., (2004). However another three areas have been selected for our preliminary study. This area is used to test the ability of the algorithm develop due to the different geographical condition. These areas have also been chosen as preliminary study for the above mentioned references. The areas are;

a) Arabian Sea
b) Mediterranean Sea
c) Atlantic Ocean

This following section is the discussion of the two main areas which is selected in this study. The section is organized as follows: Firstly, the discussion about the geographical area of Gulf of Martaban is presented. Following that, is the discussion of the geographical area of Yellow sea and nearby area. The discussion about the three geographical areas mentioned for the preliminary study is not provided. For reference and further reading of the three geographical areas, please refer back to Li et al., (2003), Gao et al., (2002), Ramaswamy et al., (2004) and Liu et al., (2004).

3.2.1 Gulf of Martaban

Figure 3.1(a) shows the map of Gulf of Martaban and nearby area. Geographically Gulf of Martaban is located at the northern Andaman Sea. Annually more than 350 million tons of sediment deposited into this area by the Ayerrarwady, Salween and Sittang rivers. In general, the Andaman Sea is a body of water to the southeast of the Bay of Bengal, south of Myanmar, west of Thailand and east of the Andaman Islands that is part of the Indian Ocean. It is roughly 1,200 km (north-south) and 650 km wide (east-west), with an area of 797,700 km^2. Its average depth