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STUDY OF THE SEASONAL AND INTERANNUAL VARIABILITY OF PHYTOPLANKTON BLOOM IN ARABIAN GULF USING MODIS DATA

Malik Mutasim Malik Gasim

This thesis is submitted in partial fulfillment of the requirements for the Degree of Master of Science in Environmental Sciences

Under the Supervision of Dr. Abdelgadir Abuelgasim

April 2016
Declaration of Original Work

I, Malik Mutasim Malik Gasim, the undersigned, a graduate at the United Arab Emirates University (UAEU), and the author of this thesis entitled “Study of the Seasonal and Interannual Variability of Phytoplankton Bloom in Arabian Gulf using MODIS Data”, hereby, solemnly declare that this thesis is my own original research work that has been done and prepared by me under the supervision of Dr. Abdelgadir Abuelgasimat UAEU. This work has not previously been presented or published, or formed the basis for the award of any academic degree, diploma or a similar title at this or any other university. Any materials borrowed from other sources (whether published or unpublished) and relied upon or included in my thesis have been properly cited and acknowledged in accordance with appropriate academic conventions. I further declare that there is no potential conflict of interest with respect to research, data collection, authorship, presentation and/or publication of this thesis.

Student’s Signature: ___________________________ Date: 08/01/2017
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Abstract

The Arabian Gulf is a semi enclosed large water body that experiences seasonal variations and reversal of its water currents flow circulation. The Gulf waters are characterized by having high primary productivity and strong phytoplankton blooms at particular seasons within the year. Phytoplankton is a base of the food chain for marine species, providing an essential food resource for aquatic life. Marine phytoplankton affects the diversity of any marine ecosystem and drives its functioning and is strongly correlated with fishery yields. The primary objectives of this research study are to answer key research questions related to phytoplankton blooms in the Arabian Gulf. The research attempts to identify the seasonal and inter-annual variations of phytoplankton blooms, the factors that affect these blooms, and the spatial distribution of such blooms within the Gulf waters using the Moderate Resolution Imaging Spectroradiometer – AQUA (MODISA) and the Advanced Scatterometer (ASCAT) satellite data. MODIS derived chlorophyll concentration (chlorophyll-a) product (as indicator of phytoplankton) and MODIS sea surface temperature product (SST) over the study area are utilized. ASCAT wind vectors are used to identify the prevailing wind direction over the study area. The major findings from this research are that observed phytoplankton concentrations in the Arabian Gulf experience wide variability from season to season each year. The onset of phytoplankton blooms in the Arabian Gulf starts in early autumn season reaching its peak at the end of the season and into the onset of the winter season. High levels of phytoplankton concentrations remain visible in the satellite data through the winter season where it starts to disappear towards the end of the season. The spring and summer seasons portray the lowest levels of phytoplankton with no apparent bloom during the study period in these seasons. The percentile increase between the minimum and maximum concentrations is almost 140%. The phytoplankton blooms in the Arabian Gulf are strongly influenced by the sea surface temperature and the prevailing winds and their directions. Phytoplankton blooms are associated with the north easterly wind regime of autumn and winter coupled by lower SST. A strong positive inverse relation between chlorophyll concentrations and sea surface temperature within the study area are observed from the satellite data. During the study period 2003-2013 a decline in the overall chlorophyll concentrations of approximately 2% - 4% is observed. This is currently assessed from only 9 to 11
observations spanning the years of the study period. This is not a statistically valid sample to make a major conclusions vis-à-vis the trend of the phytoplankton concentrations in the Arabian Gulf. To have a statistically valid sample, a minimum of 30 observations are needed from MODIS observations. However, the results are in agreement with previous studies of declining phytoplankton concentrations globally. The summary of the results of this study provided key information in regards to the study’s major research questions.

**Keywords:** Phytoplankton bloom, chlorophyll, sea surface temperature, winds currents, satellite image, Arabian Gulf Sea, MODIS, ASCAT.
الوالق النباتية هي قاعدة السلسلة الغذائية للأنواع البحرية، توفر الموارد الغذائية الأساسية للحياة المائية، وتمكن العديد من الأسماك من البقاء على قيد الحياة. والوالق النباتية البحرية تثير كذلك على تنويع النظم الإيكولوجية البحرية وتشكل عملها للاكلاع على وضع الحدود العليا لعوائد الثروة السمكية. وتريد العوامل التي تلعب دورًا هاماً في إزدهار الوالق النباتية في بحيرة الخليج يؤدي إلى وضع قرار جيد للحفاظ على الثروة السمكية في الخليل. يقدم عاملة بيانات الأنماط الصناعية أداة متى لدراسة تركيز الوالق النباتية والتوزيع المكاني والتبادل الموسمي. يوجد عاملين مفيدين جداً يمكن دراستهما عن طريق صور الأنماط الصناعية هما درجة حرارة سطح البحر وتركيز الكلوروفيل ومستوياتها. الأهداف الرئيسية لهذه الدراسة هي التحقق من وتحديد العوامل الرئيسية التي تنظم تقلب الوالق النباتية في منطقة الخليج العربي.

الخليج العربي هو مسطح مائي شبه مغلق المنفذ الوحيد له لتحديد مياهه هو المضيق الرابط مع خليج عمان والمياه المتدفقة من نهر العراق. وتتميز مياه الخليج وبحر العرب الشمالي الشرقي بالإنتاجية الأولية العالية والعوامل النباتية قوية هناك في أوقات مختلفة من السنة. يستخدم هذا البحث تركيزات الكلوروفيل والمستخراج عبر القمر الصناعي (MODISA) جنب إلى جنب مع استخدام معلومات القمر الصناعي (ASCAT) المخصصة لحركة المياه وحركة وسرعة تيارات الهواء، وكتابة درجة حرارة سطح البحر للتعرف على العوامل والأمثلة التي تنظم الأشكال المختلفة من تركيزات الكلوروفيل. النتائج الرئيسية من هذا البحث هو أن تركيزات الكلوروفيل المرصودة تبدأ فيها لزيادة في موسم الخريف وتبلغ ذروتها في أشهر الشتاء (ديسمبر و فبراير) بسبب الظروف المعتدلة من التغيرات المائية السفلى المفيدة بالرياح الشمالية إلى الشمالية الشرقية الموسمية، خلايا أكتوبر و مارس. تبدأ درجة حرارة سطح البحر في الزيادة خلال الربع حتى تصل إلى ذروتها في يوليو أو أغسطس من فصل الصيف، في الوقت نفسه تركز الكلوروفيل يشهد حالة من الضعف في يوليو في علاقة عكسية مع درجة الحرارة. درجات حرارة سطح المياه تؤثر التغير عن طريق التبريد في المستوى العلوي للمياه بالتعاون مع قانون القثافة، وتبادل الطبقية المنخفضة للمياه مع المستويات العليا و تقوم بجلب
المواد الغذائية معها إلى السطح لإطعام العوائق النباتية وتساعد على نشر العوائق النباتية فوق سطح البحر.

مفاهيم البحث الرئيسي : العوائق المائية، الكلوروفيلا، حرارة سطح البحر، التيارات الهوائية، المواس، صور الأقمار الصناعية، مياه الخليج العربي، الانتشار، الموجات المتقلبة، الكثافة، (موديس)، (إسكات).
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Special thanks go to people on Remote Sensing and GIS laboratory in UAE University who provided me with the facilities being required and conductive conditions for my Master thesis.
I dedicate this thesis work to my family, to my loving parents who never stopped short on giving me encouragement and pushed me to do the best I can. I also dedicate this work to all siblings who supported me every time I encounter some difficulty during the course of my work.
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Chapter 1: Introduction

1.1 Overview

Phytoplankton are single-celled marine microscopic organism, some of which are capable of movement through the use of flagella while others drifts with currents (Verlencar and Desai 2004). These microscopic plants range in size from 1/1000 of a millimeter to 2 millimeters and float or swim in the upper 100 m of the ocean, where they are dependent on sunlight for photosynthesis, in addition to light and oxygen, they require basic simple inorganic chemical nutrients, such as phosphate (PO$_4$) and nitrate (NO$_3$) (Verlencar and Desai 2004). They also require carbon in the form of carbon dioxide (CO$_2$), some phytoplankton, the diatoms, also requires a form of silicon (silicate, SiO$_4$) because they have a “glass-like” shell (Verlencar and Desai 2004).

The definition of phytoplankton illustrate that microscopic organism are essential to marine ecosystem and marine life. Phytoplankton are essential food resource for aquatic life, many fish survive by the eating the plankton as it is the starting point of the marine food web (Abuelgasim and Naeema, 2014). According to (Diersing, 2009) phytoplankton organisms are capable of absorbing sunlight that is necessary for growth and reproduction and other nutrients directly from the surrounding water.

For any species to bloom environmental factors such as water and air temperatures, water currents movements and salinity must be just right and essential nutrients must be available in the correct amounts.
1.2 The Importance of Phytoplankton

Since researchers studied (Danling et.al, (2002); Martinez, et. al, (2011); Babin, et. Al, (2003);Shang et. Al, (2012);Xu eT. Al, (2012)) the phytoplankton functions on ocean and marine ecosystem, they found many benefits for surrounding and remote environment. Several studies from our literature review experienced the same findings of phytoplankton benefits. Although the different locations of the studies areas had been covered and different tools had been used.

Due to the status of phytoplankton on the marine food web, we know the essential role for phytoplankton in the marine food chain. Phytoplankton contributes about 95% of primary production in the oceans, on this depends the secondary production (zooplankton) and tertiary production (fish, shellfish, mammals, etc…), Since phytoplankton serve as a basic food source for animals in the sea their presence in large numbers may indicate the abundance of commercially important fish and shellfish populations (Verlencar and Desai 2004). Two important benefits from existence and abundance of phytoplankton, the existence of phytoplankton benefit represent in basis of marine food web. The benefit of abundance represent in when the phytoplankton are plenty in one area that properly lead into richness of fish, shellfish, mammals, etc…

The importance of phytoplankton could be appear in several ways some of the phytoplankton roles played a significant perspective to the good of ecosystem, and some significant perspective of phytoplankton are came to form a hazard to environment ecosystem. They impact us in at least three ways. First, they appear to be a significant factor in controlling atmospheric carbon dioxide (CO₂), a greenhouse gas, which in turn can influence heat retention in the Earth’s atmosphere, Secondly,
the phytoplankton and bacteria are the basis of the marine food web. At this level, inorganic nutrients like phosphate, nitrate, and carbon dioxide are converted to larger more complex organic molecules necessary for life. In turn, these microscopic organisms higher in the food web, such as zooplankton, fishes and mammals. For example, bivalve shellfish (oysters, mussels, scallops, clams) almost exclusively consume phytoplankton for their food. And lastly, marine algae are important because they can produce a variety of highly toxic compounds—marine biotoxins. These compounds, some of which can be released to the surrounding water while others are retained in the phytoplankton, can enter the food web and accumulate in fish and shellfish. In most cases, fish and shellfish do not appear to be affected by these potent compounds, but organisms higher in the food web, such as marine mammals and humans, can be made ill or even die (Verlencar and Desai 2004).

We could summarize the important of phytoplankton into good influence to environment and adverse influence to the environment like below:

Good influence:

1. Phytoplankton are the basis of the marine food web, so that the availability of phytoplankton lead to the availability to the rest organisms in the food web.
2. Throughout the photosynthesis process, phytoplankton able to control carbon dioxide and greenhouse gases in the atmosphere and give back oxygen $O_2$, which it lead to a balance in Earth’s atmosphere and the environment.
3. The abundance of phytoplankton organisms in certain area consider an ideal place for marine organisms to assemble in the area to feed on phytoplankton and zooplankton so that it’s consider a source to fishing even commercially fishing.
Adverse influence:

1. Phytoplankton in sometimes under certain conditions can be toxic, in the case of overproducing. This situation of toxicity harms surrounding environment and the elements of the environment. And because of this harmful of environment the importance of phytoplankton became influence and imperative to study. This toxicity influence not only the marine ecosystem but influence the mankind, since the human is at the top of the food web which starts of phytoplankton, the highly toxic compounds, will reach to the human food table.

The term phytoplankton bloom refers to the conditions when there is a rapid increase in the number of phytoplankton and their concentration in specific geographic areas in a short period of time. In many such situations this may lead to water discoloration than the water assuming its natural color. Verlencar and Desai 2004 explains that a single microalgal species can increase in abundance until they dominate the microscopic plant community and reach such high concentrations that they discolor the water with their pigments, these “blooms” of algae are often referred to as a “red tide” although referred to as “red tide”, blooms are not only red, but can be brown, yellow, green, or milky in color. These blooms can be caused by high concentrations of toxic algal species and referred to as a “harmful algal bloom”, however non-toxic species can also bloom and harmlessly discolor the water. So in general phytoplankton blooms can have both negative and positive effects on any marine ecosystem.

Phytoplankton blooms on water bodies can cover a small area to many large square kilometers and usually have particular temporal duration of time as well as occurring
in particular season of the year (Diersing, 2009). The disappearance of the bloom is usually associated with the decline of their nutrients source and the other favorable conditions to their increase. For example, a bloom may develop after plant fertilizers containing nitrogen and phosphorus are carried into near shore waters by rainfall surface runoff. Once the nutrients in the water have been depleted by the phytoplankton organisms, the bloom usually dissipates. (Diersing, 2009)

1.3 Monitoring Phytoplankton Bloom by Satellite

Satellite data provide synoptic, long-term time serious coverage, which is ideal for the identification of bloom events, also satellite-derived chl a data can be used as a practical index for identifying phytoplankton blooms (Xu et. al 2012). Satellite data are particularly well suited for this task as they cover large areal extent, provide continuous repetitive coverage, comes in various spectral forms and the data is of good quality. The short duration repetitive coverage nature of satellite data over the oceans is of particular importance as this provides continuous coverage of a bloom event and helps track the bloom movement and dissipation.

Several studies have utilized satellite observations for monitoring phytoplankton blooms. Danling et.al (2002) used Ocean Color and Temperature Scanner (OCTS) and Sea-view Wide Field-of-view Sensor (SeaWiFS)-derived chlorophyll and AVHRR sea surface temperature to study the short-term variability of phytoplankton blooms in the northwestern Arabian Sea. The study reports an increase in biological productivity was evident in winter. Further, field data showed that in the northern Arabian sea, most of the primary productions occur below the surface during the south-west monsoon from June to September during the north-east monsoon from
October to January, the average of the primary production is higher than during the pre-monsoon from February to May. In case of Arabian Sea, the study results reveal that phytoplankton blooms coincide with the cold sea surface temperature (SST), which is in agreement with the fact that the blooms are promoted by local upwelling.

Martinez, et. al., (2011) used the Coastal Zone Color Scanner (CZCS) and SeaWiFS satellite data to study the Phytoplankton spring and fall blooms in the North Atlantic in the 1980s and 2000s. A particular emphasis was to study the difference between the spring and fall blooms during the stated periods. An additional emphasis was to study the connection between water depth stratification and seasonal phytoplankton blooms. The study investigates the variability of phytoplankton along with that of the mixed layer depth (MLD) and of the wind stress. The study’s major findings are that the amplitude of the fall and spring blooms was high during both periods, with little differences. In 2000s the spring bloom was stronger and extended further south than in 1980s. This stronger spring may results of stronger wintertime winds; the fall bloom was weaker in the 2000s and only appeared at the northern boundary of the study region.

Babin, et. al. (2003) used both SeaWIFS and AVHRR satellite data for studying if phytoplankton blooms are induced by episodes of prevailing cyclones in the Bay of Bengal. The Bay of Bengal has generally low biological productivity in comparison to the Arabian Sea, however the study major findings demonstrates that this productivity increase rapidly with the onset of cyclone events. This has been shown to be due to the strong winds during cyclones due to the mix of deep water layers thus induct nutrients to the mixed layer resulting in high nutrients levels (Vinayachandran, 2003).
Shang et al. (2012) used MODIS-Aqua chlorophyll derived product to study the phytoplankton bloom during the northeast monsoon in the Luzon Strait, in the south China Sea. The study reports that a small portion of the bloom was located near shore in the Babuyan Channel and its vicinity, and was strong and persistent for five months (October-February) which is one month earlier than the triggering time of the large offshore portion. Upwelling at the center of the Luzon Gyre contributes to the offshore bloom. The near shore bloom is substantially enhanced by nutrient input from the Cagayan River.

Xu et al (2012) used SeaWIFS satellite data between the period 1998-2006 along with profiles of temperature, salinity and wind characteristics for studying the role of wind in regulating phytoplankton blooms on the Mid-Atlantic Bight. This study used time series of satellite chlorophyll and 3-D biophysical model simulations to investigate the relative importance of the water mixing rates and light availability for phytoplankton populations in the study area. The study reports that late fall-winter bloom is the most recurrent and largest phytoplankton bloom in the MAB. The fall-winter bloom is fueled by the replenishment of nutrients to the euphotic zone once the summer thermal stratification has been disrupted. Wind forcing also has a significant role on the timing and magnitude of the offshore spring bloom. They found increase mixing will increase nutrients availability but decrease light availability. Moreover the phytoplankton dynamics in the shelf-break front region are found to be more sensitive to the wind-induced mixing.

The previous short review demonstrates that satellite data have effectively been used for studying marine ecosystems and phytoplankton blooms. The studies also showed that exists a suit of several earth observation satellites that can be used for mapping and monitoring phytoplankton blooms in the oceans and seas.
The basic premise in the use of multispectral observations for mapping phytoplankton blooms is that the chlorophyll within the phytoplankton reflects in a particular manner that can be detected using multispectral sensors. Through the multispectral transformation of satellite measured radiation it is possible to develop chlorophyll indices as indicators of the presence of phytoplankton. The higher the magnitude of these indices within a pixel the higher the amount of phytoplankton present within that pixel.

The previous studies have also shown that phytoplankton blooms are influenced by many factors working together. The prevailing wind, speed and direction strongly influence the water currents upwelling and mixing, sea surface temperature is also another major factor that affects the blooms. Salinity, season of the year and shape of the sea, are other importantly influencing factors.

1.4 Global Trends of Phytoplankton Blooms

In the past decade several research studies have attempted to identify the major trends in the biogeochemical composition of the world oceans and the global trends of phytoplankton concentrations (Rousseaux and Gregg 2015; Marinov et. al. 2013; Boyce and Lewis, 2010). Most of these studies have reported major declines in the amount of phytoplankton concentrations world-wide. For example, Rousseaux and Gregg (2015) reports that diatoms, the largest type of phytoplankton algae, have declined more than 1 percent per year from 1998 to 2012 globally, with significant losses occurring in the North Pacific, North Indian and Equatorial Indian oceans. In addition, the negative trends on phytoplankton trends are particularly pronounced in tropical and subtropical oceans, where increasing stratification limits nutrient supply. On the other hand regional climate variability can induce variation around these
long-term trends, and coastal processes such as land runoff may modify phytoplankton trends in near shore waters.

Furthermore, most of the studies suggest that these changes are generally related to climatic and oceanographic variability and particularly to increasing SST over the past century. These results provide a larger context for recently observed declines in remotely sensed phytoplankton concentrations are consistent with the hypothesis that increasing ocean warming is contributing to a restructuring of marine ecosystems, with implications for biogeochemical cycling, fishery yields and ocean circulation (Daniel and Marlon, 2010).

While rising SST and warming temperatures might be attributed to the decline, the loss of large amount of phytoplankton results in further SST increase. Phytoplankton needs carbon dioxide for the process of photosynthesis which is usually absorbed from the atmosphere. With less amounts of planktons present less carbon dioxide is absorbed and hence resulting in further rise in global temperature.

This research investigates the factors regulating the seasonal and inter-annual variations, and the long term trends in phytoplankton blooms in the Arabian Gulf using multi-temporal satellite observations. With alarming studies on the decline of global phytoplankton concentrations it is imperative that the levels of phytoplankton in the Gulf are continuously monitored and the factors that regulate their blooms or decline are properly identified and studied. Such information is importantly needed for government policy development and decision support.
Chapter 2: Research Problem, Objectives and Study Area

2.1 Factors from Previous Studies

Phytoplankton blooms in the global oceans and seas are influenced by a series of environmental, physical and climatic factors. Oceans primary biological productivity is sometimes influenced by the monsoon seasons (McClanahan, 1998), circulation, upwelling and eddies (Meyer and others, 2002), nutrients (Kyewalyanga et. al. 2007), irradiance and temperature (Bowman and others, 2003), bottom topography that might cause upwelling (Galliene and symythe-wright, 2005), growth rates (Cloern and others, 2014), grazing (Calbet, 2008) and water column stability (Barlow and others, 2007).

The bulletin issued by the United Nations Environment Program (UNEP) (2015) reported that in the West Indian Ocean (WIO) regional series of factors influence phytoplankton blooms,

1) Monsoon circulation, primary productivity in the WIO region is subjected to two alternating and distinctive seasons, the southern and northern monsoons, which have a marked effect on air and water temperature, wind, rainfall and phytoplankton biomass. The prevailing winds during the monsoons are a particularly important influencing factor on water circulation. They affect the distribution of nutrients and marine organisms as well as biological processes, changing wave action and affecting a wide range of human activities.

2) Ocean currents and circulation are important features that strongly influence the availability of nutrients and the distribution of phytoplankton through upwelling
process. Upwelling is the process through which deep nutrient-rich waters are brought up into the surface layers.

3) Irradiance and temperature, irradiance is a major driving force for photosynthesis; it warms the surface waters of the oceans, thereby regulating the water temperature. Both temperature and irradiance vary with the seasons of the year. Temperature is an important environmental parameter that influences biological processes in the ocean, and various studies have demonstrated that phytoplankton community structure varies in a regular, predictable pattern with temperature, especially in temperature regions.

4) Nutrients, nutrients availability (especially nitrogen and phosphorus) is one of the primary factors that control the distribution of phytoplankton communities in the WIO region, while silicate not to be limiting for this region. Nutrients distribution varies both horizontally and vertically in the water column.

Obtaining knowledge about the factors that influences the phytoplankton biomasses in West Indian Ocean (WIO) are very important because the WIO regions consider the nearest ocean to our study area and the similarity on aspects between these two areas both in the case of oceanography and temperature. Also, obtaining information from specialized globally organization like (UNEP) summarized hundreds of studies about which factors influence the phytoplankton blooms worldwide and give many valuable information about phytoplankton bloom, there for we can comfortably rely on (UNEP) study.

The UNEP report stresses four key primary factors influencing phytoplankton blooms worldwide. These factors include:
1. Wind currents
2. Ocean or water currents as influenced by the wind currents
3. Sea surface temperature
4. Sea water salinity

2.2 Study Area

The water body under study in this research is the Arabian Gulf. The Arabian Gulf is a semi-enclosed sea located between 24° N - 30° N latitude and 48° E - 56° E longitudes, the total area is around 239,000 km² and has an average depth of 40m. It has an average length of 1000 km and an approximate width of 350 km, the Gulf is connected to the Sea of Oman and the northern Arabian Sea through the Strait of Hormuz, the major river source into the Gulf is the Shatt-Al-Arab, flowing from the Euphrates, Tigris in Iraq and Karun rivers in Iran (Abuelgasim and Alhosani, 2014).

Figure 2.1: Map of the Arabian Gulf
(source: http://gulfnews.com/news/uae/society/how-google-is-showing-arabian-gulf-on-maps-1.1560237)
2.3 Research Issues

The Arabian Gulf waters and the northern Arabian Sea are characterized by high primary productivity and strong phytoplankton blooms at different times of the year (Tang et. al 2002) and (Das et. al. 1980). However, little is known about the factors and mechanisms that regulate these variations of the phytoplankton blooms and the inter-annual variations of chlorophyll concentrations in the Gulf waters.

This research study investigates the physical and environmental factors regulating these seasonal and inter-annual variations, and the long term trends in phytoplankton blooms in the Arabian Gulf. The rationale is that with many studies reporting a global decline of phytoplankton concentrations it is imperative that the levels of phytoplankton in the Gulf are continuously monitored and the factors that regulate their blooms or decline are properly identified and studied. Such information would prove to be valuable for government policy development and decision support.

The research will make use of a set of multi-temporal remotely sensed data for mapping the phytoplankton blooms in the Arabian Gulf, their geographical locations, seasonal and inter-annual variability. Remotely sensed data is an ideal tool for this investigation as it provides accurate, continuous, and repetitive coverage over the study area. Furthermore, the data is freely available to allow the performance of this study.

Within this context the research study tries to address and answer key questions that shed the light vis-à-vis the phytoplankton blooms in the Arabian Gulf. These key questions can be summarized as:
1. Are there any phytoplankton blooms in Arabian Gulf Sea?

This is a key fundamental question through which the research study tries to assess the biological productivity of the Arabian Gulf.

2. When is the phytoplankton bloom usually occurring in Arabian Gulf Sea?

This question tries to understand the temporal variability of the Arabian Gulf phytoplankton blooms in terms of their seasonal patterns and duration.

3. Where is phytoplankton bloom occurring in Arabian Gulf Sea?

While the areal extent of the Arabian Gulf is too small in comparison with the neighboring water bodies, it is important to identify the geographical location of the blooms. Through this it will be possible to identify the location of the initial bloom onsets, pattern of travel and their impact on the blooms of the Sea of Oman.

4. What are the key main factors that influences the phytoplankton blooms in the Arabian Gulf?

The research study will attempt to identify the key factors that regulate the blooms within the study area. While previous studies have identified many factors, the focus of this study would be to study the impact of only three factors in the Arabian Gulf phytoplankton blooms. Namely, wind currents and patterns, water currents and sea surface temperature. To investigate other more factors would be beyond the scope of this study.
Through providing answers to these research questions it will be possible to shed more light on the status of the biological productivity of the Arabian Gulf waters. Strong correlations have been reported in the literature between fishery yields and phytoplankton concentrations (Friedlandet. Al, 2012). As such, information about factors affecting seasonal and inter-annual variations of phytoplankton concentrations, location of blooms and their spatial distribution would prove to be extremely useful for the UAE fishing industry. Further more information about changing trends in such concentrations, naturally or human induced, would provide key information for setting specialized governmental policies to address any serious and alarming trends.
Chapter 3: Satellite Data and Image Processing

3.1 Data Collection

3.1.1 Chlorophyll and Sea Surface Temperature (SST) Data

Several satellites data are currently available that provides extensive coverage spectrally and temporally over the study area. This research uses data that comes from the Moderate Resolution Imaging Spectroradiometer (MODIS) (http://modis.gsfc.nasa.gov/about/) for mapping the phytoplankton concentrations and sea surface temperature. Furthermore, wind vectors data over the study area are obtained from the Advanced Scatterometer (ASCAT) for identifying the wind direction pattern.

MODIS is one of the key sensor instruments aboard the Terra and Aqua satellites collection data over the entire globe every 1-2 days (Letelier and Abbott 1996). MODIS collects spectral data over the entire globe in 36 spectral bands in the visible, near-infra-red and short wave infra-red parts of the electromagnetic spectrum. Furthermore, MODIS collects data also in the thermal portion of the spectrum. The choice of the spectral ranges of MODIS spectral data was based on the different data applications intended. What is of concern in this study is the spectral range of MODIS that deals with ocean color observations.
### Table 3.1: Ocean Color and Phytoplankton Bands

<table>
<thead>
<tr>
<th>Primary Use</th>
<th>Band</th>
<th>Band width (nms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ocean Color/Phytoplankton/Biogeochemistry</td>
<td>8</td>
<td>405 - 420</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>438 - 448</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>483 - 493</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>526 - 536</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>546 - 556</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>662 - 672</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>673 - 683</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>743 - 753</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>862 - 877</td>
</tr>
</tbody>
</table>

(Source: [http://modis.gsfc.nasa.gov/about/specifications.php#1](http://modis.gsfc.nasa.gov/about/specifications.php#1))

The choice to use MODIS data for the analysis in this research was guided by several factors. First, MODIS data covers the entire period of the intended study period 2003-2013 and this removes the need of sensor’s radiometric normalization in case of the use of more than one sensor. Secondly, MODIS data are the latest additions to the suite of ocean color data, are freely available and easy to access. Thirdly, MODIS chlorophyll estimation algorithms have been extensively tested and calibrated in various parts of the world making them the most availably accurate products. Finally, MODIS chlorophyll estimation products come with a reliability quality assessment and validation indicators.

The study uses the already generated chlorophyll estimated global product for mapping the phytoplankton blooms over the Arabian Gulf. Generally MODIS spectral radiance measurements are processed to ground reflectance and then further processed into chlorophyll concentrations using chlorophyll estimation algorithms ([http://oceancolor.gsfc.nasa.gov/cms/atbd#](http://oceancolor.gsfc.nasa.gov/cms/atbd#)). The chlorophyll concentrations are indicative of the presence of phytoplankton. Each pixel in a MODIS chlorophyll
image represents the estimated chlorophyll amount derived (mg/m$^3$). The algorithm for estimating chlorophyll is:

Chlorophyll a = $10^{(a_0 + a_1X + a_2X^2 + a_3X^3 + a_4X^4)}$

Where:

$X = \log_{10} \left( \frac{R_1}{R_2} \right)$

$R_1$ = blue band reflectance

$R_2$ = green band reflectance

$a_0 = 0.2424$

$a_1 = -2.7423$

$a_2 = 1.8017$

$a_3 = 0.0015$

$a_4 = -1.2280$

(http://oceancolor.gsfc.nasa.gov/cms/atbd#)

Table 3.2: Sea Surface Temperature Bands

<table>
<thead>
<tr>
<th>Primary Use</th>
<th>Band</th>
<th>Band width (nms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface/Cloud</td>
<td>31</td>
<td>10.780 - 11.280</td>
</tr>
<tr>
<td>Temperature</td>
<td>32</td>
<td>11.770 - 12.270</td>
</tr>
</tbody>
</table>

(Source: http://oceancolor.gsfc.nasa.gov/cms/atbd/sst/)

The sea surface temperature algorithm makes use of the long wave MODIS bands 31 and 32 (table3.2) for estimating the surface temperature. In summary the brightness temperature values are derived from the by the inversion of the observed radiance versus blackbody temperature relationship. A complete description of the SST algorithm can be found in (http://oceancolor.gsfc.nasa.gov/cms/atbd/sst/), (Brown and Minnett, 1999) and (Kilpatrick, 2001).
3.1.2 Advanced Scatterometer Data (ASCAT)

The ASCAT was launched in 2006 by the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT). The primary objectives of ASCAT are the measurement of wind speed and direction over the oceans (http://www.eumetsat.int/website/home/Satellites/CurrentSatellites/Metop/MetopDesign/ASCAT/index.html). ASCAT has also been used effectively for studying polar ice, soil moisture and vegetation.

In essence ASCAT is a real aperture radar system operating at the C-band of 5.255 GHz. The instrument transmits well known characteristic microwave pulses towards the sea and ocean surfaces. The wind over the ocean surfaces cause small scale disturbances of the sea surface which modify its radar backscattering characteristics in a particular way. These backscattering properties are well known and are dependent on both the wind speed over the sea and the direction of the wind, with respect to the point from which the sea surface is observed. More details about ASCAT can be found at (http://www.eumetsat.int/website/home/Satellites/CurrentSatellites/Metop/MetopDesign/ASCAT/index.html; http://www.remss.com/missions/ascat) and (Figa-Saldaña et. al. 2002; Ricciardulli et. al. 2012).
3.1.3 Data Access

MODIS chlorophyll and SST data were obtained from (http://oceancolor.gsfc.nasa.gov/). The data comes in 4 km format and represents the mean average monthly chlorophyll concentration and average monthly SST covering the period of 2003-2013. In addition the mean annual chlorophyll concentrations and SST were also acquired for the years 2003-2013. Figure (3.1) and (3.2) show sample of the acquired chlorophyll concentration image and the SST over the Arabian Gulf.

Figure 3.1: 2003 Mean Annual Chlorophyll Concentration
(source: (http://oceancolor.gsfc.nasa.gov/))
Figure 3.2: 2003 Mean Annual Sea Surface Temperature
(source: http://oceancolor.gsfc.nasa.gov/)

Figure 3.3: ASCAT Wind Speed and Direction
(source: http://manati.star.nesdis.noaa.gov/datasets/ASCATData.php/)
ASCAT data were accessed from (http://manati.star.nesdis.noaa.gov/datasets/ASCATData.php). Figure (3.3) shows a sample of the wind direction and speed over the Arabian Gulf in 2013/03/13.

Two primary assumptions guided the use of ASCAT data and its access. First, wind patterns (speed and direction) are periodic, seasonal and repeat themselves on an annual basis. Two selecting every other day within a month to identify the wind direction is fairly good representative of the prevailing wind direction for that month. Based on this assumption ASCAT data was accessed for the last 3 years 2011-2013. For each month during this period, starting from the first day of the month every other day data was accessed to be analyzed.

3.2 Image Data Processing

MODIS chlorophyll concentration and the SST images are generated globally. It was necessary to crop the image data and focus on the study area only. From these cropped images of chlorophyll concentrations and SST, the mean monthly chlorophyll concentrations and SST values were calculated for the study period (2003-2013). Similarly was the average annual chlorophyll concentrations and SST for the same time period. In addition to the monthly and annual data, seasonal data for the years 2011, 2012 and 2013 were used to calculate the seasonal corresponding values. However, there are missing data in the seasonal chlorophyll concentration in some season especially (summer 2011, 2012 and 2013), so the missing data were excluded and created a mask for data that are available.
The ASCAT data were visually analyzed for the period 2011-2013. For each month about 12-15 image maps of wind directions were visually analyzed. The analysis was focused on determining the dominant wind direction over the Gulf waters. The wind direction that is occurring more than 50% of the time was assumed to be the prevailing wind direction for that month for the study area.
Chapter 4: Methodology

The chlorophyll concentration data were used to retrieve the annual and monthly average time series (2003-2013) and seasonal product (2011-2012-2013) were downloaded from http://oceancolor.gsfc.nasa.gov. The acquired data covered the entire globe. The first step in the image processing was to create a database image file of all acquired data using the software GEOMATICA. This was followed by extracting the image data over the study area only and cropping the rest of the images.

Furthermore, an image mask over the gulf waters was manually digitized to cover the water within the study area only. Every effort and care was taken to insure that the mask does not include any land pixels from the different scattered islands or coastal land areas. Using the software statistical analysis tools, the area under the mask was analyzed to calculate the mean and standard deviations of the chlorophyll concentrations annually (2003-2013) and mean of chlorophyll concentrations seasonally (2011, 2012, and 2013), and monthly chlorophyll concentrations for each month for the period (2003-2013).

A similar process was followed for the SST images. The temperature annually (2003-2013), seasonally (2011-2012-2013) and monthly time series were extracted from http://oceancolor.gsfc.nasa.gov/ at 4 km resolution. The study area cropped from the global products. The mean and standard deviation SST annually (2003-2013) seasonally (2011, 2012, 2013) and monthly were all calculated.
ASCAT data were acquired and processed visually. For each month within the study approximately 15 images of the ASCAT wind vectors data was acquired. The visual inspection comprised of careful examination of the wind vectors directions of the wind currents. The resulting analysis for each month revealed the prevailing wind direction pattern of that month from the frequently occurring direction within the 15 images. This process was deemed satisfactory in identifying the overall wind direction pattern over the gulf waters.

The extracted mean chlorophyll concentrations and SST for each month of the study period were plotted to graphically show the pattern of chlorophyll concentrations variability and trend monthly, seasonally and annually. In addition, the chlorophyll and SST images were used to visually analyze and interpret of the data. This aimed to identify the basic trends of the movements and spatial distribution of chlorophyll blooms in Arabian Gulf Sea during each month (if any) during the study period. This visual assessment was harmonized in parallel with the images of SST and wind vector data. The process was aimed to comparatively analyze the variations of chlorophyll concentrations with respect to SST and wind vector data and identify, if any, of these factors have an effect of the blooms onset, movement or variability.
Chapter 5: Results and Discussions

The figures (5.1A—5.12B) below show the results of the monthly, seasonal and annual chlorophyll concentrations versus the SST for the years 2003-2013 of the study period. Table (5.1) shows the dominant wind direction pattern as extracted from the ASCAT data. The graphs also show trend lines of the chlorophyll concentrations and SST.

5.1 2003 Monthly SST and Chlorophyll Concentration Relationship and Seasonal SST and Chlorophyll Concentration Relationship

Figure 5.1A: 2003 Monthly SST (Sea Surface Temperature) and Chlorophyll Concentration
Figure 5.1B: 2003 Seasonal SST (Sea Surface Temperature) and Chlorophyll Concentration

5.2 2004 Monthly SST and Chlorophyll Concentration Relationship and Seasonal SST and Chlorophyll Concentration Relationship

Figure 5.2A: 2004 Monthly SST (Sea Surface Temperature) and Chlorophyll Concentration
5.3 2005 Monthly SST and Chlorophyll Concentration Relationship and Seasonal SST and Chlorophyll Concentration Relationship
5.4 2006 Monthly SST and Chlorophyll Concentration Relationship and Seasonal SST and Chlorophyll Concentration Relationship
5.5 2007 Monthly SST and Chlorophyll Concentration Relationship and Seasonal SST and Chlorophyll Concentration Relationship

![2006 Seasonal SST and Chlorophyll Concentration](image)

Figure 5.4B: 2006 Seasonal SST (Sea Surface Temperature) and Chlorophyll Concentration

![2007 Monthly SST and Chlorophyll Concentration](image)

Figure 5.5A: 2007 Monthly SST (Sea Surface Temperature) and Chlorophyll Concentration

\[
\begin{align*}
\text{Linear (chlor)} & : y = 0.008x + 0.9781 \\
\text{Linear (sst)} & : y = 3.6032x + 18.421
\end{align*}
\]
Figure 5.5B: 2007 Seasonal SST (Sea Surface Temperature) and Chlorophyll Concentration

5.6 2008 Monthly SST and Chlorophyll Concentration Relationship and Seasonal SST and Chlorophyll Concentration Relationship

Figure 5.6A: 2008 Monthly SST (Sea Surface Temperature) and Chlorophyll Concentration
5.7 2009 Monthly SST and Chlorophyll Concentration Relationship and Seasonal SST and Chlorophyll Concentration Relationship

Figure 5.6B: 2008 Seasonal SST (Sea Surface Temperature) and Chlorophyll Concentration

Figure 5.7A: 2009 Monthly SST (Sea Surface Temperature) and Chlorophyll Concentration
Figure 5.7B: 2009 Seasonal SST (Sea Surface Temperature) and Chlorophyll Concentration

5.8 2010 Monthly SST and Chlorophyll Concentration Relationship and Seasonal SST and Chlorophyll Concentration Relationship

Figure 5.8A: 2010 Monthly SST (Sea Surface Temperature) and Chlorophyll Concentration
5.9 2011 Monthly SST and Chlorophyll Concentration Relationship and Seasonal SST and Chlorophyll Concentration Relationship

Figure 5.9A: 2011 Monthly SST (Sea Surface Temperature) and Chlorophyll Concentration

Figure 5.8B: 2010 Seasonal SST (Sea Surface Temperature) and Chlorophyll Concentration

\[
\begin{align*}
\text{sst} & \quad \text{°C} \\
\text{chlor} & \quad \text{mg/m}^3
\end{align*}
\]

\[
\begin{align*}
y &= 3.0639x + 20.018 \\
y &= 0.0373x + 0.8645
\end{align*}
\]

\[
\begin{align*}
y &= 0.2888x + 24.98 \\
y &= -0.011x + 0.9968
\end{align*}
\]
5.10 2012 Monthly SST and Chlorophyll Concentration Relationship and Seasonal SST and Chlorophyll Concentration Relationship

Figure 5.10A: 2012 Monthly SST (Sea Surface Temperature) and Chlorophyll Concentration

\[ y = 0.8326x + 22.256 \]
\[ y = -0.0586x + 1.3013 \]
5.11 2013 Monthly SST and Chlorophyll Concentration Relationship and Seasonal SST and Chlorophyll Concentration Relationship

Figure 5.10B: 2012 Seasonal SST (Sea Surface Temperature) and Chlorophyll Concentration

Figure 5.11A: 2013 Monthly SST (Sea Surface Temperature) and Chlorophyll Concentration
5.12 11-Year Mean Annual SST and Chlorophyll Concentration Relationship and Mean Seasonal SST and Chlorophyll Concentration Relationship
Figure 5.12B: 11-Year Mean Seasonal SST and Chlorophyll Concentration (2003-2013)

Table 5.1: Monthly wind direction in Arabian Gulf (2003-2013)

<table>
<thead>
<tr>
<th>Month</th>
<th>Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>Northeast</td>
</tr>
<tr>
<td>February</td>
<td>Northeast</td>
</tr>
<tr>
<td>March</td>
<td>Northeast</td>
</tr>
<tr>
<td>April</td>
<td>Southwest</td>
</tr>
<tr>
<td>May</td>
<td>Southwest</td>
</tr>
<tr>
<td>June</td>
<td>Southwest</td>
</tr>
<tr>
<td>July</td>
<td>Southwest</td>
</tr>
<tr>
<td>August</td>
<td>Southwest</td>
</tr>
<tr>
<td>September</td>
<td>Southwest</td>
</tr>
<tr>
<td>October</td>
<td>Northeast</td>
</tr>
<tr>
<td>November</td>
<td>Northeast</td>
</tr>
<tr>
<td>December</td>
<td>Northeast</td>
</tr>
</tbody>
</table>
5.13 Monthly Chlorophyll Concentrations Pattern

A careful examination of the chlorophyll concentrations pattern for example from all figures, (look at Appendix C Monthly SST and Chlorophyll Concentration) indicates that the Arabian Gulf experiences a high biological productivity period and phytoplankton blooms due to a significant rise of chlorophyll concentrations during the autumn-winter period. Chlorophyll concentrations are at their lowest levels during the summer month of August in the years of the study period. These levels start to rise significantly by the month of September reaching a peak by the end of the period of November to January. The data does not show a clear indicator of a particular peak month for the phytoplankton blooms.

Phytoplankton bloom peaks during the study period were almost equally distributed between the months of November, December and January. This can be theorized to be due to the SST and perhaps significant wind currents leading to upwelling of cold water currents. In the majority of the months with the peak chlorophyll concentrations the SST was the lowest. However, this preliminary observation needs to be investigated further.

The figures also display a strong inverse correlation between the levels of chlorophyll concentrations and SST. Rising chlorophyll concentrations levels are associated with decreasing SST during all the years of the study period. This is not surprising as previous studies (Tang and Kawamura, 2002; Martinez and Antoine 2011; Sarangi and Chauhan, 2005; Maryam and Imen, 2012) have described inverse relations between the two. This is likely due to the upwelling of cold water currents into the surface bringing high concentrations of nutrients for the phytoplankton to blooms.
From the visual analysis of the MODIS chlorophyll concentration images (APPENDIX A and C) it follows that by early September high concentration levels are geographically located in the northern and western side of the Gulf. By late September, the shallow southern areas along the UAE start to display some levels of concentration as well. It’s only by October where the eastern side of the Gulf displays high levels of chlorophyll concentrations. The overall concentration levels in the Gulf begin to decline by February. This pattern is repeated on annual basis (figures not shown for brevity).

The monthly variations of the chlorophyll blooms, its geographic location and spatial distribution observed in MODIS data can be explained by the movement of the wind and water currents. ASCAT data show two primary wind seasons that dominate the area. Namely, north easterly and south westerly wind regimes(see table 5.1) above. The north easterly wind regime is dominant in the autumn and winter and is associated with higher levels of chlorophyll concentrations, while the south westerly wind regime is dominant in the spring and summer and is associated with lower to no phytoplankton blooms. This wind regime has an impact on the geographical and spatial distribution of the phytoplankton blooms in the area.

In late summer (August) dense and nutrient rich bottom water current outflow follows southwards aided by the north easterly wind currents through the western side of the gulf and along the coastline of the UAE (Abuelgasim and Alhosani, 2014). This leads to the display of slightly elevated levels of chlorophyll concentrations (< 1.0 mg/m³) in early September along the western side of the Gulf. During the period September-November the surface currents flow into the Gulf and are now weaker while the bottom currents up-well and continue flowing out of the
Arabian Gulf into the Sea of Oman further displaying higher concentration levels in most of the Gulf area (Ahmed and Sultan, 1991).

5.14 Seasonal Chlorophyll Concentrations Pattern

Figures (5.12B) show the seasonal chlorophyll and SST patterns for the study period. The seasonal data displayed shows similar pattern as the monthly ones. The autumn and winter seasons are the ones with higher levels of phytoplankton blooms and biological productivity of the gulf waters (see APPENDIX A.b). The winter season is much more frequently being the one with the highest phytoplankton levels in comparison to the autumn. Note that the autumn season represents the beginning of the onset of the phytoplankton blooms and have months with still lower concentration levels of chlorophyll, while the winter season represent mostly higher levels of concentrations that starts to dissipate by February. This likely explains why in most of the years investigated the winter season shows higher levels of biological activity in comparison to the autumn season.

5.15 Annual Chlorophyll Concentrations Pattern

Figure (5.12A) shows the mean annual chlorophyll and SST levels (also APPENDIX A.a). With the exceptions of years 2006, 2008 and 2009, the variability of chlorophyll concentrations levels between 2003 and 2013 displays a declining level of more than 0.2 mg/m³. Note that years 2008 and 2009 are associated with a severe episode of a red-tide event that engulfed large areas of the UAE coastal areas, the Strait of Hormuz and the Sea of Oman.
The trend line of the chlorophyll concentrations indicates about 2% decline during the study period. Note that this is based only on 11 observations from 2003-2013 and might not be a statistically valid value, however. It can be safely assumed that during the period 2003-2013 phytoplankton levels have declined by an approximate value of 2%. Note the years 2006, 2008 and 2009 represented an anomaly with the red tide event (Maryam and Imen, 2012). Figure (5.13) shows the phytoplankton pattern should 2006, 2008 and 2009 not be included in the results.

![Figure 5.13: Mean Annual Chlorophyll Concentrations Excludes Red Tide Years (2003-2013)](image)

With the exclusion of the years 2006, 2008 and 2009 the chlorophyll concentrations trend for the remaining eight years still displays a declining pattern, however. The rate of decline is much stronger amounting to approximately twice the previous amount with the red tide years included. This is not surprising as red tide events displays large amount of chlorophyll in the gulf waters suggesting a lower decline.
Figures 5.14 (a-e) below show the relationship between the gulf waters SST and chlorophyll concentrations for the period 2003-2013. Different trend formats are shown. As has been reported earlier there is a strong inverse relation between SST and chlorophyll concentrations (see APPENDIX B). As SST raises the concentrations declines and as the SST moves lower there is an associated increase in the chlorophyll concentrations. SST plays an important role in regulating phytoplankton blooms in the gulf waters.

\[
y = -1.1419x + 28.22 \\
R^2 = 0.1967
\]

Figure 5.14A: Linear Relationship between SST and Chlorophyll Concentrations in Arabian Gulf (2003-2013).
Figure 5.14B: Exponential Relationship between SST and Chlorophyll Concentrations in Arabian Gulf (2003-2013).

\[ y = 28.241e^{-0.042x} \]
\[ R^2 = 0.1962 \]

Figure 5.14C: Logarithmic Relationship between SST and Chlorophyll Concentrations in Arabian Gulf (2003-2013).

\[ y = -1.291\ln(x) + 27.069 \]
\[ R^2 = 0.1965 \]
The inverse relation is clearly displayed in the linear trend-line. With the exception of the polynomial trend line the r-squares shown between the two variables did not exceed 0.2. Note that such statistics are not very reliable as only 11 observations are
used; however, what is of importance here is the shape of the relationship between the two variables.

![Figure 5.14F: Relationship between Monthly Average SST and Chlorophyll Concentrations in Arabian Gulf (2003-2013).]

\[ y = -0.0536x + 2.4905 \]
\[ R^2 = 0.3768 \]

The figure above shows the inverse relationship between chlorophyll concentration and monthly average SST during the period of 2003 to 2013. This figure addressed the same result between chlorophyll concentration and SST in prior figures.
Chapter 6: Conclusion and Future Directions

This study attempted to address key issues regarding phytoplankton blooms in the Arabian Gulf using remotely sensed data. The research results provide various insights into the seasonal and inter-annual variations of the biological productivity of the Arabian Gulf. Phytoplankton concentrations in the Arabian Gulf experience wide variability from season to season each year. The onset of phytoplankton blooms in the Arabian Gulf starts in early autumn season reaching its peak at the end of the season and into the onset of the winter season. High levels of phytoplankton concentrations remain visible in the satellite data through the winter season where it starts to disappear towards the end of the season. The spring and summer seasons portray the lowest levels of phytoplankton with no apparent bloom during the study period in these seasons. The percentile increase between the minimum and maximum concentrations is almost 140%.

The phytoplankton blooms in the Arabian Gulf are strongly influenced by the sea surface temperature and the prevailing wind directions. Phytoplankton blooms are associated with the north easterly wind regime of autumn and winter coupled by lower SST. During the study period 2003-2013 there is a decline in the overall chlorophyll concentrations of approximately 2% - 4%. This is currently assessed from only 9 to 11 observations spanning the years of the study period. This is not a statistically valid sample to make a major conclusions vis-à-vis the trend of the phytoplankton concentrations in the Arabian Gulf. To have a statistically valid sample, a minimum of 30 observations are needed from MODIS observations. However, the results are in agreement with previous studies of declining phytoplankton concentrations globally. The summary of the results of this study provided key information in regards to the study’s major research questions.
The study focused on the SST and the wind regime direction as the primary factors that influence the phytoplankton blooms in the Arabian Gulf. There are many other factors that are likely to play a major role in phytoplankton blooms and should be coupled with the previously discussed factors. Factors such as water salinity, the bathymetry of the area, and being an open or closed or semi-closed water bodies. These factors are important and would likely have an impact directly or indirectly on the water currents upwelling and spatial distribution of any bloom. At present studying the contribution of these factors are beyond the research work of this study and perhaps future studies should focus in incorporating these additional factors.

Future research can also attempt to build statistical relationships between SST and chlorophyll concentrations. At present it will not be possible with merely 11 MODIS observations.

With declining global phytoplankton levels it will be prudent that such levels in the Arabian Gulf are continuously monitored and assessed and the impact on the UAE fishing industry carefully assessed. This should be an issue of concern as with expected climatic changes and the rise of global temperatures the impacts on marine ecosystems can be profound.

Remotely sensed data over oceans and water bodies proved to be a useful tool for assessing the biological productivity and mapping phytoplankton blooms. Such data provide continuous repetitive coverage globally with a high temporal resolution making them the ideal tool for further studies in the Arabian Gulf. However, the lack of long term historical record is only available through the use of data that comes from multiple sensors. The major issues with using such kind of data are that not all the sensor characteristics are similar. This requires extensive statistical radiometric calibration and normalization between the different sensors data.
References


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Appendices

Appendix A: Satellite Images

A. Satellite Images: Mean Annual SST and Chlorophyll Concentration

A.1 2003 Mean Annual SST and Chlorophyll Concentration Satellite Images

Figure 7.1A1: 2003 Mean Annual Sea Surface Temperature

Figure 7.2A1: 2003 Mean Annual Chlorophyll Concentration
A.2 2004 Mean Annual SST and Chlorophyll Concentration Satellite Images

Figure 7.1A2: 2004 Mean Annual Sea Surface Temperature

Figure 7.2A2: 2004 Mean Annual Chlorophyll Concentration
A.3 2005 Mean Annual SST and Chlorophyll Concentration Satellite Images

Figure 7.1A3: 2005 Mean Annual Sea Surface Temperature

Figure 7.2A3: 2005 Mean Annual Chlorophyll Concentration
A.4 2006 Mean Annual SST and Chlorophyll Concentration Satellite Images

Figure 7.1A4: 2006 Mean Annual Sea Surface Temperature

Figure 7.2A4: 2006 Mean Annual Chlorophyll Concentration
A.5 2007 Mean Annual SST and Chlorophyll Concentration Satellite Images

Figure 7.1A5: 2007 Mean Annual Sea Surface Temperature

Figure 7.2A5: 2007 Mean Annual Chlorophyll Concentration
A.6 2008 Mean Annual SST and Chlorophyll Concentration Satellite Images

Figure 7.1A6: 2008 Mean Annual Sea Surface Temperature

Figure 7.2A6: 2008 Mean Annual Chlorophyll Concentration
A.7 2009 Mean Annual SST and Chlorophyll Concentration Satellite Images

Figure 7.1A7: 2009 Mean Annual Sea Surface Temperature

Figure 7.2A7: 2009 Mean Annual Chlorophyll Concentration
A.8 2010 Mean Annual SST and Chlorophyll Concentration Satellite Images

Figure 7.1A8: 2010 Mean Annual Sea Surface Temperature

Figure 7.2A8: 2010 Mean Annual Chlorophyll Concentration
A.9 2011 Mean Annual SST and Chlorophyll Concentration Satellite Images

Figure 7.1A9: 2011 Mean Annual Sea Surface Temperature

Figure 7.2A9: 2011 Mean Annual Chlorophyll Concentration
A.10 2012 Mean Annual SST and Chlorophyll Concentration Satellite Images

Figure 7.1A10: 2012 Mean Annual Sea Surface Temperature

Figure 7.2A10: 2012 Mean Annual Chlorophyll Concentration
A.11 2013 Mean Annual SST and Chlorophyll Concentration Satellite Images

Figure 7.1A11: 2013 Mean Annual Sea Surface Temperature

Figure 7.2A11: 2013 Mean Annual Chlorophyll Concentration
B. Satellite Images: Mean Seasonal SST and Chlorophyll Concentration

B.1 2003-2013 Winter Mean SST and Chlorophyll Concentration

Figure 7.1B1: 2003-2013 Winter Mean Sea Surface Temperature

Figure 7.2B1: 2003-2013 Winter Mean Chlorophyll Concentration
B.2 2003-2013 Spring Mean SST and Chlorophyll Concentration

Figure 7.1B2: 2003-2013 Spring Mean Sea Surface Temperature

Figure 7.2B2: 2003-2013 Spring Mean Chlorophyll Concentration
B.3 2003-2013 Summer Mean SST and Chlorophyll Concentration

Figure 7.1B3: 2003-2013 Summer Mean Sea Surface Temperature

Figure 7.2B3: 2003-2013 Summer Mean Chlorophyll Concentration
B.4 2003-2013 Autumn Mean SST and Chlorophyll Concentration

Figure 7.1B4: 2003-2013 Autumn Mean Sea Surface Temperature

Figure 7.2B4: 2003-2013 Autumn Mean Chlorophyll Concentration
C. Sea Surface Temperature Color Band

![Sea Surface Temperature Color Band](image)

Figure 7.1C: Sea Surface Temperature Color Band

D. Chlorophyll Concentration Color Band

![Chlorophyll a concentration Color Band](image)

Figure 7.1D: Chlorophyll Concentration Color Band
Appendix B: Table Of Measurements

The SST is measured in degree Centigrade (°C) and the chlorophyll concentration is measured in milligrams per cubic meter (mg / m³).

A. Annual Sea Surface Temperature and Chlorophyll Concentration

A.1 2003 and 2004 SST and Chlorophyll concentration

Table 1.A1: 2003 SST and Chlorophyll Concentration Measurements

<table>
<thead>
<tr>
<th>2003</th>
<th>Chlorophyll Concentration (mg/m³)</th>
<th>SST(°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>1.62246</td>
<td>21.49174569</td>
</tr>
<tr>
<td>February</td>
<td>1.54751</td>
<td>20.45773355</td>
</tr>
<tr>
<td>March</td>
<td>1.032007</td>
<td>20.47470728</td>
</tr>
<tr>
<td>April</td>
<td>0.577803</td>
<td>23.90832006</td>
</tr>
<tr>
<td>May</td>
<td>0.563038</td>
<td>27.10085509</td>
</tr>
<tr>
<td>June</td>
<td>0.682997</td>
<td>30.24132037</td>
</tr>
<tr>
<td>July</td>
<td>0.375479</td>
<td>32.16983206</td>
</tr>
<tr>
<td>August</td>
<td>0.567951</td>
<td>33.86306453</td>
</tr>
<tr>
<td>September</td>
<td>1.032768</td>
<td>32.58595314</td>
</tr>
<tr>
<td>October</td>
<td>1.616274</td>
<td>31.02496365</td>
</tr>
<tr>
<td>November</td>
<td>1.665231</td>
<td>27.80078848</td>
</tr>
<tr>
<td>December</td>
<td>1.620257</td>
<td>23.62389385</td>
</tr>
</tbody>
</table>

Table 2.A1: 2004 SST and Chlorophyll Concentration Measurements

<table>
<thead>
<tr>
<th>2004</th>
<th>Chlorophyll Concentration (mg/m³)</th>
<th>SST (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>1.828763</td>
<td>21.74086</td>
</tr>
<tr>
<td>February</td>
<td>1.646185</td>
<td>20.72195</td>
</tr>
<tr>
<td>March</td>
<td>1.11661</td>
<td>21.80369</td>
</tr>
<tr>
<td>April</td>
<td>0.600226</td>
<td>23.46619</td>
</tr>
<tr>
<td>May</td>
<td>0.640935</td>
<td>26.29978</td>
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<tr>
<td>June</td>
<td>0.572804</td>
<td>29.00228</td>
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<tr>
<td>July</td>
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<tr>
<td>August</td>
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<td>September</td>
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<td>October</td>
<td>1.310712</td>
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</tr>
<tr>
<td>November</td>
<td>2.080519</td>
<td>28.80291</td>
</tr>
<tr>
<td>December</td>
<td>1.078462</td>
<td>23.70452</td>
</tr>
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</table>
### A.2 2005 and 2006 SST and Chlorophyll Concentration

Table 1.A2: 2005 SST and Chlorophyll Concentration Measurements

<table>
<thead>
<tr>
<th>2005</th>
<th>Chlorophyll Concentration (mg/m$^3$)</th>
<th>SST(°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>1.732758</td>
<td>20.645471</td>
</tr>
<tr>
<td>February</td>
<td>1.383219</td>
<td>19.491408</td>
</tr>
<tr>
<td>March</td>
<td>0.750173</td>
<td>20.620042</td>
</tr>
<tr>
<td>April</td>
<td>0.55546</td>
<td>23.050215</td>
</tr>
<tr>
<td>May</td>
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Table 2.A2: 2006 SST and Chlorophyll Concentration Measurements

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A.3 2007 and 2008 SST and Chlorophyll Concentration

Table 1.A3: 2007 SST and Chlorophyll Concentration Measurements

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Table 2.A3: 2008 SST and Chlorophyll Concentration Measurements

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A.4 2009 and 2010 SST and Chlorophyll Concentration

Table 1.A4: 2009 SST and Chlorophyll Concentration Measurements

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Table 2.A4: 2010 SST and Chlorophyll Concentration Measurements

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A.5 2011 and 2012 SST and Chlorophyll Concentration

Table 1.A5: 2011 SST and Chlorophyll Concentration Measurements

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<tbody>
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<td>1.222575</td>
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Table 2.A5: 2012 SST and Chlorophyll Concentration Measurements

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### Table 1.A6: 2013 SST and Chlorophyll Concentration Measurements

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### Table 2.A6: Mean Interannual SST and Chlorophyll Concentration Measurements

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B. Seasonal Sea Surface Temperature and Chlorophyll Concentration

Table 1.B: 2003 Seasonal SST and Chlorophyll Concentration Measurements

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<td>Summer</td>
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Table 2.B: 2004 Seasonal SST and Chlorophyll Concentration Measurements

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<th>SST (°C)</th>
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Table 3.B: 2005 Seasonal SST and Chlorophyll Concentration Measurements

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Table 4.B: 2006 Seasonal SST and Chlorophyll Concentration Measurements

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<th>SST (°C)</th>
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Table 5.B: 2007 Seasonal SST and Chlorophyll Concentration Measurements

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Table 6.B: 2008 Seasonal SST and Chlorophyll Concentration Measurements

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<th>SST (°C)</th>
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Table 7.B: 2009 Seasonal SST and Chlorophyll Concentration Measurements

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<th>SST (°C)</th>
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<td>Spring</td>
<td>0.94068</td>
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<td>Summer</td>
<td>0.626094333</td>
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Table 8.B: 2010 Seasonal SST and Chlorophyll Concentration Measurements

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<th>SST (°C)</th>
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<tr>
<td>Winter</td>
<td>1.233937333</td>
<td>21.605708</td>
</tr>
<tr>
<td>Spring</td>
<td>0.653210333</td>
<td>26.399068</td>
</tr>
<tr>
<td>Summer</td>
<td>0.551642</td>
<td>33.132835</td>
</tr>
<tr>
<td>Autumn</td>
<td>1.392062</td>
<td>29.574033</td>
</tr>
</tbody>
</table>

Table 9.B: 2011 Seasonal SST and Chlorophyll Concentration Measurements

<table>
<thead>
<tr>
<th>Season</th>
<th>Chlorophyll Concentration (mg/m³)</th>
<th>SST (°C)</th>
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</thead>
<tbody>
<tr>
<td>Winter</td>
<td>1.464965667</td>
<td>20.21932286</td>
</tr>
<tr>
<td>Spring</td>
<td>0.746481667</td>
<td>26.5118531</td>
</tr>
<tr>
<td>Summer</td>
<td>0.467785</td>
<td>32.69231885</td>
</tr>
<tr>
<td>Autumn</td>
<td>1.022818333</td>
<td>28.57282351</td>
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</tbody>
</table>

Table 10.B: 2012 Seasonal SST and Chlorophyll Concentration Measurements

<table>
<thead>
<tr>
<th>Season</th>
<th>Chlorophyll Concentration (mg/m³)</th>
<th>SST (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>1.504645667</td>
<td>21.7273646</td>
</tr>
<tr>
<td>Spring</td>
<td>0.931430333</td>
<td>26.0184541</td>
</tr>
<tr>
<td>Summer</td>
<td>0.496811667</td>
<td>32.9062328</td>
</tr>
<tr>
<td>Autumn</td>
<td>0.748103</td>
<td>30.467583</td>
</tr>
</tbody>
</table>
Table 11.B: 2013 Seasonal SST and Chlorophyll Concentration Measurements

<table>
<thead>
<tr>
<th>Season</th>
<th>Chlorophyll Concentration (mg/m3)</th>
<th>SST (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>1.246819333</td>
<td>20.92461716</td>
</tr>
<tr>
<td>Spring</td>
<td>0.574460333</td>
<td>25.98715798</td>
</tr>
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<td>Summer</td>
<td>0.445633667</td>
<td>32.4096485</td>
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<tr>
<td>Autumn</td>
<td>1.0399</td>
<td>28.59805827</td>
</tr>
</tbody>
</table>

Table 12.B: 11-Year Mean Seasonal SST and Chlorophyll Concentration Measurements

<table>
<thead>
<tr>
<th>Season</th>
<th>Chlorophyll Concentration (mg/m3)</th>
<th>SST (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>17.090513</td>
<td>20.99764347</td>
</tr>
<tr>
<td>Spring</td>
<td>8.250275</td>
<td>26.18170949</td>
</tr>
<tr>
<td>Summer</td>
<td>6.903939</td>
<td>32.68542726</td>
</tr>
<tr>
<td>Autumn</td>
<td>14.502318</td>
<td>29.25925187</td>
</tr>
</tbody>
</table>
### C. 11-Year Mean Monthly SST and Chlorophyll Concentration Measurements

Table 1.C: 11-Year Mean Monthly SST and Chlorophyll Concentration Measurements

<table>
<thead>
<tr>
<th>Month</th>
<th>Chlorophyll Concentration (mg/m³)</th>
<th>SST (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>1.571432</td>
<td>20.59844</td>
</tr>
<tr>
<td>February</td>
<td>1.596977</td>
<td>20.51165</td>
</tr>
<tr>
<td>March</td>
<td>1.007115</td>
<td>22.21755</td>
</tr>
<tr>
<td>April</td>
<td>0.596885</td>
<td>25.63417</td>
</tr>
<tr>
<td>May</td>
<td>0.646075</td>
<td>28.59587</td>
</tr>
<tr>
<td>June</td>
<td>0.700814</td>
<td>30.69489</td>
</tr>
<tr>
<td>July</td>
<td>0.556332</td>
<td>32.90543</td>
</tr>
<tr>
<td>August</td>
<td>0.625746</td>
<td>33.08519</td>
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<tr>
<td>September</td>
<td>1.120694</td>
<td>31.53729</td>
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<tr>
<td>October</td>
<td>1.362928</td>
<td>29.05238</td>
</tr>
<tr>
<td>November</td>
<td>1.471556</td>
<td>25.6665</td>
</tr>
<tr>
<td>December</td>
<td>1.49264</td>
<td>23.58371</td>
</tr>
</tbody>
</table>
Appendix C: Monthly SST and Chlorophyll Concentration

A. 2003 Monthly SST and Chlorophyll Concentration

Figure 8.1A1: January 2003 SST       Figure 8.1A2: January 2003 Chl Concentration

Figure 8.2A1: February 2003 SST      Figure 8.2A2: February 2003 Chl Concentration

Figure 8.3A1: March 2003 SST         Figure 8.3A2: March 2003 Chl Concentration
Figure 8.4A1: April 2003 SST  Figure 8.4A2: April 2003 Chl Concentration

Figure 8.5A1: May 2003 SST  Figure 8.5A2: May 2003 Chl Concentration

Figure 8.6A1: June 2003 SST  Figure 8.6A2: June 2003 Chl Concentration

Figure 8.7A1: July 2003 SST  Figure 8.7A2: July 2003 Chl Concentration
B. 2004 Monthly SST and Chlorophyll Concentration

Figure 8.12A1: December 2003 SST  Figure 8.12A2: December 2003 Chl Concentration

Figure 8.1B1: January 2004 SST  Figure 8.1B2: January 2004 Chl Concentration

Figure 8.2B1: February 2004 SST  Figure 8.2B2: February 2004 Chl Concentration
C. 2005 Monthly SST and Chlorophyll Concentration
Figure 8.6C1: June 2005 SST       Figure 8.6C2: June 2005 Chl Concentration

Figure 8.7C1: July 2005 SST       Figure 8.7C2: July 2005 Chl Concentration

Figure 8.8C1: August 2005 SST      Figure 8.8C2: August 2005 Chl Concentration

Figure 8.9C1: September 2005 SST   Figure 8.9C2: September 2005 Chl Concentration
Figure 8.10C1: October 2005 SST  Figure 8.10C2: October 2005 Chl Concentration

Figure 8.11C1: November 2005 SST  Figure 8.11C2: November 2005 Chl Concentration

Figure 8.12C1: December 2005 SST  Figure 8.12C2: December 2005 Chl
D. 2006 Monthly SST and Chlorophyll Concentration

Figure 8.1D1: January 2006 SST    Figure 8.1D2: January 2006 Chl Concentration

Figure 8.2D1: February 2006 SST    Figure 8.2D2: February 2006 Chl Concentration

Figure 8.3D1: March 2006 SST       Figure 8.3D2: March 2006 Chl Concentration

Figure 8.4D1: April 2006 SST       Figure 8.4D2: April 2006 Chl Concentration
E. 2007 Monthly SST and Chlorophyll Concentration

Figure 8.1E1: January 2007 SST    Figure 8.1E2: January 2007 Chl Concentration

Figure 8.2E1: February 2007 SST    Figure 8.2E2: February 2007 Chl Concentration

Figure 8.3E1: March 2007 SST    Figure 8.3E2: March 2007 Chl Concentration

Figure 8.4E1: April 2007 SST    Figure 8.4E2: April 2007 Chl Concentration
F. 2008 Monthly SST and Chlorophyll Concentration

Figure 8.1F1: January 2008 SST  Figure 8.1F2: January 2008 Chl Concentration

Figure 8.2F1: February 2008 SST  Figure 8.2F2: February 2008 Chl Concentration

Figure 8.3F1: March 2008 SST  Figure 8.3F2: March 2008 Chl Concentration

Figure 8.4F1: April 2008 SST  Figure 8.4F2: April 2008 Chl Concentration
Figure 8.5F1: May 2008 SST          Figure 8.5F2: May 2008 Chl Concentration

Figure 8.6F1: June 2008 SST       Figure 8.6F2: June 2008 Chl Concentration

Figure 8.7F1: July 2008 SST         Figure 8.7F2: July 2008 Chl Concentration

Figure 8.8F1: August 2008 SST     Figure 8.8F2: August 2008 Chl Concentration
Figure 8.9F1: September 2008 SS  Figure 8.9F2: September 2008 Chl Concentration

Figure 8.10F1: October 2008 SST  Figure 8.10F2: October 2008 Chl Concentration

Figure 8.11F1: November 2008 SST  Figure 8.11F2: November 2008 Chl Concentration

Figure 8.12F1: December 2008 SST  Figure 8.12F2: December 2008 Chl Concentration
G. 2009 Monthly SST and Chlorophyll Concentration

Figure 8.1G1: January 2009 SST  Figure 8.1G2: January 2009 Chl Concentration

Figure 8.2G1: February 2009 SST  Figure 8.2G2: February 2009 Chl Concentration

Figure 8.3G1: March 2009 SST  Figure 8.3G2: March 2009 Chl Concentration

Figure 8.4G1: April 2009 SST  Figure 8.4G2: April 2009 Chl Concentration
Figure 8.5G1: May 2009 SST  Figure 8.5G2: May 2009 Chl Concentration

Figure 8.6G1: June 2009 SST  Figure 8.6G2: June 2009 Chl Concentration

Figure 8.7G1: July 2009 SST  Figure 8.7G2: July 2009 Chl Concentration

Figure 8.8G1: August 2009 SST  Figure 8.8G2: August 2009 Chl Concentration
Figure 8.9G1: September 2009 SST        Figure 8.9G2: September 2009 Chl Concentration

Figure 8.10G1: October 2009 SST   Figure 8.10G2: October 2009 Chl Concentration

Figure 8.11G1: November 2009 SST   Figure 8.11G2: November 2009 Chl Concentration

Figure 8.12G1: December 2009 SST   Figure 8.12G2: December 2009 Chl Concentration
H. 2010 Monthly SST and Chlorophyll Concentration

Figure 8.1H1: January 2010 SST  Figure 8.1H2: January 2010 Chl Concentration

Figure 8.2H1: February 2010 SST  Figure 8.2H2: February 2010 Chl Concentration

Figure 8.3H1: March 2010 SST  Figure 8.3H2: March 2010 Chl Concentration

Figure 8.4H1: April 2010 SST  Figure 8.4H2: April 2010 Chl Concentration
Figure 8.5H1: May 2010 SST
Figure 8.5H2: May 2010 Chl Concentration

Figure 8.6H1: June 2010 SST
Figure 8.6H2: June 2010 Chl Concentration

Figure 8.7H1: July 2010 SST
Figure 8.7H2: July 2010 Chl Concentration

Figure 8.8H1: August 2010 SST
Figure 8.8H2: August 2010 Chl Concentration
I. 2011 Monthly SST and Chlorophyll Concentration
Figure 8.5I1: May 2011 SST
Figure 8.5I2: May 2011 Chl Concentration

Figure 8.6I1: June 2011 SST
Figure 8.6I2: June 2011 Chl Concentration

Figure 8.7I1: July 2011 SST
Figure 8.7I2: July 2011 Chl Concentration

Figure 8.8I1: August 2011 SST
Figure 8.8I2: August 2011 Chl Concentration
Figure 8.9I1: September 2011 SST          Figure 8.9I2: September 2011 Chl Concentration

Figure 8.10I1: October 2011 SST       Figure 8.10I2: October 2011 Chl Concentration

Figure 8.11I1: November 2011 SST        Figure 8.11I2: November 2011 Chl Concentration

Figure 8.12I1: December 2011 SST       Figure 8.12I2: December 2011 Chl Concentration
J. 2012 Monthly SST and Chlorophyll Concentration

Figure 8.1J1: January 2012 SST         Figure 8.1J2: January 2012 Chl Concentration

Figure 8.2J1: February 2012 SST      Figure 8.2J2: February 2012 Chl Concentration

Figure 8.3J1: March 2012 SST           Figure 8.3J2: March 2012 Chl Concentration

Figure 8.4J1: April 2012 SST            Figure 8.4J2: April 2012 Chl Concentration
Figure 8.9J1: September 2012 SST  
Figure 8.9J2: September 2012 Chl Concentration

Figure 8.10J1: October 2012 SST  
Figure 8.10J2: October 2012 Chl Concentration

Figure 8.11J1: November 2012 SST  
Figure 8.11J2: November 2012 Chl Concentration

Figure 8.12J1: December 2012 SST  
Figure 8.12J2: December 2012 Chl Concentration
K. 2013 Monthly SST and Chlorophyll Concentration

Figure 8.1K1: January 2013 SST   Figure 8.1K2: January 2013 Chl Concentration

Figure 8.2K1: February 2013 SST   Figure 8.2K2: February 2013 Chl Concentration

Figure 8.3K1: March 2013 SST     Figure 8.3K2: March 2013 Chl Concentration

Figure 8.4K1: April 2013 SST     Figure 8.4K2: April 2013 Chl Concentration
Figure 8.9K1: September 2013 SST
Figure 8.9K2: September 2013 Chl Concentration

Figure 8.10K1: October 2013 SST
Figure 8.10K2: October 2013 Chl Concentration

Figure 8.11K1: November 2013 SST
Figure 8.11K2: November 2013 Chl Concentration

Figure 8.12K1: December 2013 SST
Figure 8.12K2: December 2013 Chl Concentration