TEMPORAL AND SPATIAL CHANGES OF PRIMARY PRODUCTIVITY IN THE SEA OF MARMARA OBTAINED BY REMOTE SENSING

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Approval of the Thesis

TEMPORAL AND SPATIAL CHANGES OF PRIMARY PRODUCTIVITY IN THE SEA OF MARMARA OBTAINED BY REMOTE SENSING

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ABSTRACT

TEMPORAL AND SPATIAL CHANGES OF PRIMARY PRODUCTIVITY IN THE SEA OF MARMARA OBTAINED BY REMOTE SENSING

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Temporal and spatial variations in the Sea of Marmara based on monthly averages of chlorophyll a, which is the major indicator of phytoplankton biomass and primary production, recorded by SeaWiFS and MODIS-Aqua sensors at nearly 100 stations have been analyzed for the period of 1997-2007. Majority of phytoplankton blooms occur during the winter and spring seasons, followed by a smaller secondary bloom during the fall season. The majority of high magnitude blooms occur at the Eastern part of the Sea which may be attributed to an increase in the amount of discharge of water contaminated with nutrients originating on land where the industries are located.

The correlations between monthly averages of sea surface temperature (SST) and corresponding chlorophyll a values are statistically significant (inverse) at 1% level, where r= -0.53 and the equation of the fitted model is:

Chlorophyll a = 7.09199 – 0.215402* SST

This correlation is expected because a relative decrease in SST is an indicative of upwelling and vertical mixing which are the primary processes for the formation of phytoplankton blooms.
We have also found that monthly averages of chlorophyll a recorded by SeaWiFS and MODIS-Aqua are nearly identical and either data set can be used in place of the other.

Keywords: Primary Productivity, Sea of Marmara, Remote Sensing, Chlorophyll a, SeaWiFS, MODIS-Aqua.

ÖZ

MARMARA DENİZİ' NDE BİRİNCİL ÜRETİMİN YERE VE ZAMANA BAĞLI OLARAK DEĞİŞİMİNİN UZAKTAN ALGILAMA YÖNTEMİYLE İZLENMESİ

İkis, Didem
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Bu çalışmada, SeaWiFS ve MODIS-Aqua sensörleri tarafından 1997-2007 yılları arasında toplanmış aylık klorofil a verileri kullanılmıştır. 100' e yakın örnekleme istasyonundan alınan klorofil a değerleri fitoplankton biyokütlesi ve birincil üretimin en önemli göstergesidir. En kayda değer fitoplankton artışı, kış ve ilkbahar mevsiminde gözlemlenmiştir. Bu büyük artışı, sonbaharda meydana gelen küçük bir artış takip etmektedir. Marmara Denizi'nin doğu kıyıları, en yüksek fitoplankton artışlarına sahne olmaktadır. Sanayi bölgelerinden denize akan atık sular, yüksek miktarda besin tuzu içerdiğinden bu yüksek artışların nedeni olabilir. Aylık deniz suyu sıcaklığı ve klorofil a değerleri arasında yapılan regresyon analizi, bu iki parametrenin ters orantılı ve %1 ölçüsünde istatistiksel olarak anlamlı olduğunu ortaya çıkarmıştır. Bu analize uygun modeli ortaya koyan denklem aşağıdaki gibidir (r= -0.53):

Chlorophyll a = 7.09199 – 0.215402* SST

Deniz suyu sıcaklığındaki azalma denizin alt kesimindeki soğuk su tabakasının yüzeye çıkmasının ve düşey karışımın bir işaretidir. Bu durum da birincil üretimdeki büyük artışların nedenidir.

Bunların haricinde aylık klorofil a değerleri arasında yapılan analizler, SeaWiFS and MODIS-Aqua sensörlerinin birbirleriyle çok uyumlu olduğunu ve datalarının birlikte kullanılabileceğini ortaya koymuştur.

Anahtar Sözcükler: Birincil Üretim, Marmara Denizi, Uzaktan Algılama, Klorofil a, SeaWiFS, MODIS-Aqua.

This thesis is dedicated to the memory of My Father, Haşim İkis.

ACKNOWLEDGEMENTS

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CHAPTER 1

INTRODUCTION

In this study we present our findings about spatial and temporal variations of chlorophyll a concentrations measured by remote sensing in the Sea of Marmara during 1997-2007 period.

The name of the Marmara draws its origin from Greek word for marble (*marmaros*). It is 280 km long from northeast to southwest and nearly 80 km wide at its greatest width. Its area is 11,350 km^2 and its average depth is about 494 m and maximum depth is 1,355 m. The Sea of Marmara is an inland sea located at the North-Western part of Turkey. It is connected to Black Sea via the Bosporus Strait from the North and to Aegean Sea via Dardanelles straight from the South (Figure 1.1).

Figure 1.1 The Sea of Marmara (URL 1).

The water masses coming from both Black Sea and Mediterranean Sea hold the basin of the Sea of Marmara. Brackish waters (22-26 ppt salinity) forming the thin surface layer, sourced by Black Sea, are separated from subhalocline waters of Mediterranean Sea (38.5-38.6 ppt salinity) (Unluata *et al.*, 1990; Besiktepe, 1991). Previous studies have shown that Bosporus input (Istanbul and Black Sea load), vertical mixing through stratification, diffusion and upwelling via eddy formation are the main nutrient sources of the Sea of Marmara (Besiktepe *et al.*, 1994; Polat and Tugrul, 1995; Tugrul and Polat, 1995).

Total annual loads of total phosphorus, total nitrate and total organic carbon entering to the Sea of Marmara, through the current originated from the Black Sea, are 35, 64 and 77%, respectively (Tugrul and Polat, 1995). Annual input of river originated total nitrate and total organic compounds flowing from the Black Sea into the Sea of Marmara are about three times those flowing from the Sea of Marmara into the Black Sea (Polat and Tugrul, 1995). As stated by

Tugrul *et al.* (1995), “pollution discharges from Istanbul (40-65% of the total anthropogenic discharges) have secondary importance for the nutrient and organic carbon pools of the Marmara Sea; however, the land-based chemical pollution has drastically modified the ecosystems of coastal margins and semi-enclosed bays (e.g. Golden Horn, Izmit and Gemlik) where water exchanges with the open sea are limited.”

1.1 REMOTE SENSING

As defined by Sabins (1997) Remote sensing is “the science of acquiring, processing, and interpreting images, and related data, obtained from aircraft and satellites that record the interaction between matter and electromagnetic radiation.”

In employing remote sensing techniques there are 4 important factors to be considered: (Everett and Simonett, 1976)

1. Spatial Resolution is the minimum distance between two objects at which the images of the objects appear distinct and separate.
2. Spectral Resolution shows the location and the number of the spectral bands recorded by a satellite sensor.
3. Radiometric Resolution is the ability of quantifying the range of electromagnetic energy detected by satellite sensor.
4. Temporal Resolution shows the frequency of detection of the sampling area.

One of the first attempts to take pictures of a remote area has been made from a balloon by French photographer Gaspard Felix Tournachon in 1859. Even though he was only partially successful in achieving his aim, his experiments caught the attention of the military.

As a result the military personnel began to gather intelligence by mounting cameras on balloons, planes and even pigeons (URL 2).

The techniques of exploring the earth’s surface from the space were developed after the Soviet Union successfully launched Sputnik I in 1957. The ability of Sputnik I to gather remote sensing data was limited to telemetric verification of exact locations on the earth’s surface (URL 3).

The Coastal Zone Color Scanner (CZCS) which was launched in 1978 and continued operating until 1986 was the first sensor that could detect variations in phytoplankton pigments (Hovis *et al.*, 1980). The principle behind this detection is that when the phytoplankton biomass is high, phytoplankton containing chlorophyll a absorbs light in blue and red regions of visible spectrum. Thus an increase in phytoplankton concentration changes the color of the ocean from red, blue to green (Figure 1.2). The low concentration of phytoplankton biomass turns the ocean color into blue.

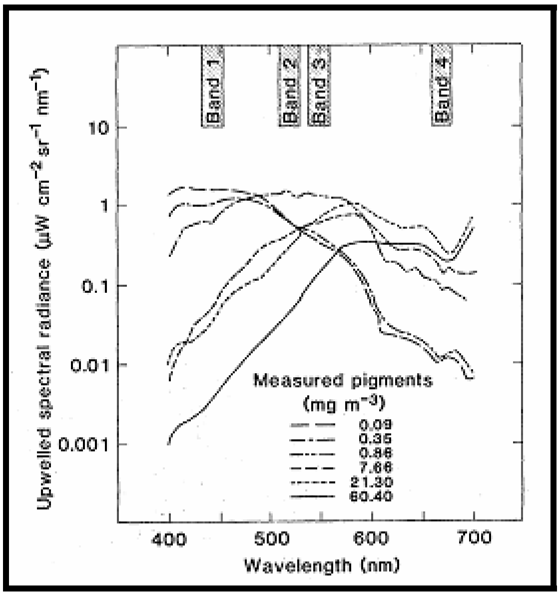


Figure 1.2 Spectra of upwelled radiance measured just beneath the sea surface at different pigment concentrations. Spectra corresponding to the two highest pigment concentrations were measured in Chesapeake Bay, and the others were measured in the Gulf of Mexico. The hatched areas represent the positions of CZCS spectral bands 1 through 4 (Hovis *et al.*, 1980).

The criteria explained above have been the governing principle for the sensors launched after CZCS. 10 sensors which are currently operating are shown in Table 1.1.

Table 1.1 Current Ocean-Color Sensors (URL 4)

Sensor	Agency	Satellite	Launch Date	Swath (km)	Resolution (m)	Bands	Spectral Coverage (nm)	Orbit
COCTS	CNSA (China)	HY-1B (Korea)	11 Apr. 2007	1400	1100	10	402-12,500	Polar
CZI	CNSA (China)	HY-1B (Korea)	11 Apr. 2007	500	250	4	433-695	Polar
MERIS	ESA (Europe)	ENVISAT (Europe)	11 Mar. 2002	1150	300/1200	15	412-1050	Polar
MMRS	CONAE (Argen.)	SAC-C (Argen.)	21 Nov. 2000	360	175	5	480-1700	Polar
MODIS-Aqua	NASA (USA)	Aqua (EOS-PM1)	4 May 2002	2330	1000	36	405-14,385	Polar
MODIS-Terra	NASA (USA)	Terra (EOS-AM1)	18 Dec. 1999	2330	1000	36	405-14,385	Polar
OCM	ISRO (India)	IRS-P4 (India)	26 May 1999	1420	350	8	402-885	Polar
OSMI	KARI (Korea)	KOMPSAT (Korea)	20 Dec. 1999	800	850	6	400-900	Polar
PARASOL	CNES (France)	Myriade Series	18 Dec. 2004	2100	6000	9	443-1020	Polar
SeaWiFS	NASA (USA)	OrbView-2 (USA)	1 Aug. 1997	2806	1100	8	402-885	Polar

Considerable improvements in measuring techniques have been made regarding these sensors. For example, SNR (signal-to-noise ratio), spectral and radiometric resolution and calibration stability monitoring of MODIS-Aqua have been greatly improved (Easias *et al.*, 1998). All these advancements have enabled us to assess more accurately the nature of spatial and temporal variations in phytoplankton biomass inferred from chlorophyll a concentrations.

In this study, we have analyzed chlorophyll a concentration data measured by SeaWiFS and MODIS-Aqua sensors. There have been several empirically-derived band ratio algorithms to calculate chlorophyll a using the measurements obtained by these sensors (O'Reilly, 1998; O'Reilly, 2000).

The default algorithms used for chlorophyll a calculation by MODIS-Aqua and SeaWiFS sensors are OC3 and OC4, respectively (URL 5),

where:

OC3:

$$C_a = 10^{(0.283-2.753R+1.457R^2+0.659R^3-1.403R^4)},$$

$$\text{Where } R = \log_{10}\left(\frac{R_{rs}443>R_{rs}488}{R_{rs}551}\right)$$

and

OC4:

$$C_a = 10^{(0,366-3.067R+1.930R^2+0.649R^3-1.532R^4)},$$

$$\text{Where } R = \log_{10}\left(\frac{R_{rs}443>R_{rs}490 > R_{rs}510}{R_{rs}555}\right)$$

OC: Oceanic Chlorophyll a

Numbers used in algorithms: Number of bands used.

R: Reflectance

C_a: Chlorophyll a concentration

These algorithms have been tested worldwide. Gregg *et al.* (2004) showed that chlorophyll a calculated from SeaWiFS data set taken near the coastal regions produces less precise results (r^2 = 0.60) than in open ocean regions (r^2 = 0.72). That is because coastal regions are defined as Case 2 water which includes much more colored dissolved organic matter than chlorophyll a. These dissolved matters increase uncertainties in chlorophyll a calculations. Open ocean gives highly consistent results because it is described as Case 1 water having only chlorophyll a as colored substance.

Furthermore, special algorithms have been developed to improve quality of satellite data taken in Mediterranean Sea, Black Sea, and Baltic Sea (Darecki *et al.*, 2004; Sancak *et al.*, 2005; Volpe *et al.*, 2007).

Satellite technology provides a rich data set which the marine scientist can use to calculate temporal and spatial patterns of chlorophyll a concentrations for several years (Field *et al.*, 1998; Nezlin *et al.*, 2003; Beman *et al.*, 2005).

1.2 PRIMARY PRODUCTIVITY PATTERNS AND DYNAMICS

Primary productivity is the rate of production of organic compounds from carbon dioxide and water, principally through the process of photosynthesis. Algae, phytoplankton species and some vascular plants such as sea grasses are the main organisms responsible for primary production. Phytoplankton produces 90-96% of oceanic carbohydrates, since these are photosynthetic organisms; the amount of chlorophyll a concentration measured by satellite sensors is a good indicator of primary productivity.

Algae include prokaryotic bacteria (eubacteria and archaea) and three eukaryote categories (the green, brown and red algae) (Purves *et al.*, 2001).

Among the major phytoplankton species are diatoms, dinoflagellates and coccolithophores (Figure 1.3).

Remote sensing technique enables us to make long-term and large-scale monitoring by extending our observations beyond the *in situ* sampling. One of the most important applications of remote sensing in aquatic sciences has been the detection and monitoring of Red Tides characteristics of which are the huge increases of the some dinoflagellate species which can reach millions of organisms per liter. As a result, the surface of the water turns into reddish-brown or red color due to the light reflectance of the accessory pigments. Because some dinoflagellates produce toxic material as a by-product of metabolic processes, Red Tides can be harmful to other species living in the same area. Thus in addition to intrinsic scientific value, the study of this phenomenon is extremely important because of resulting economic devastation (Richardson, 1996; Stumpf, 2001).

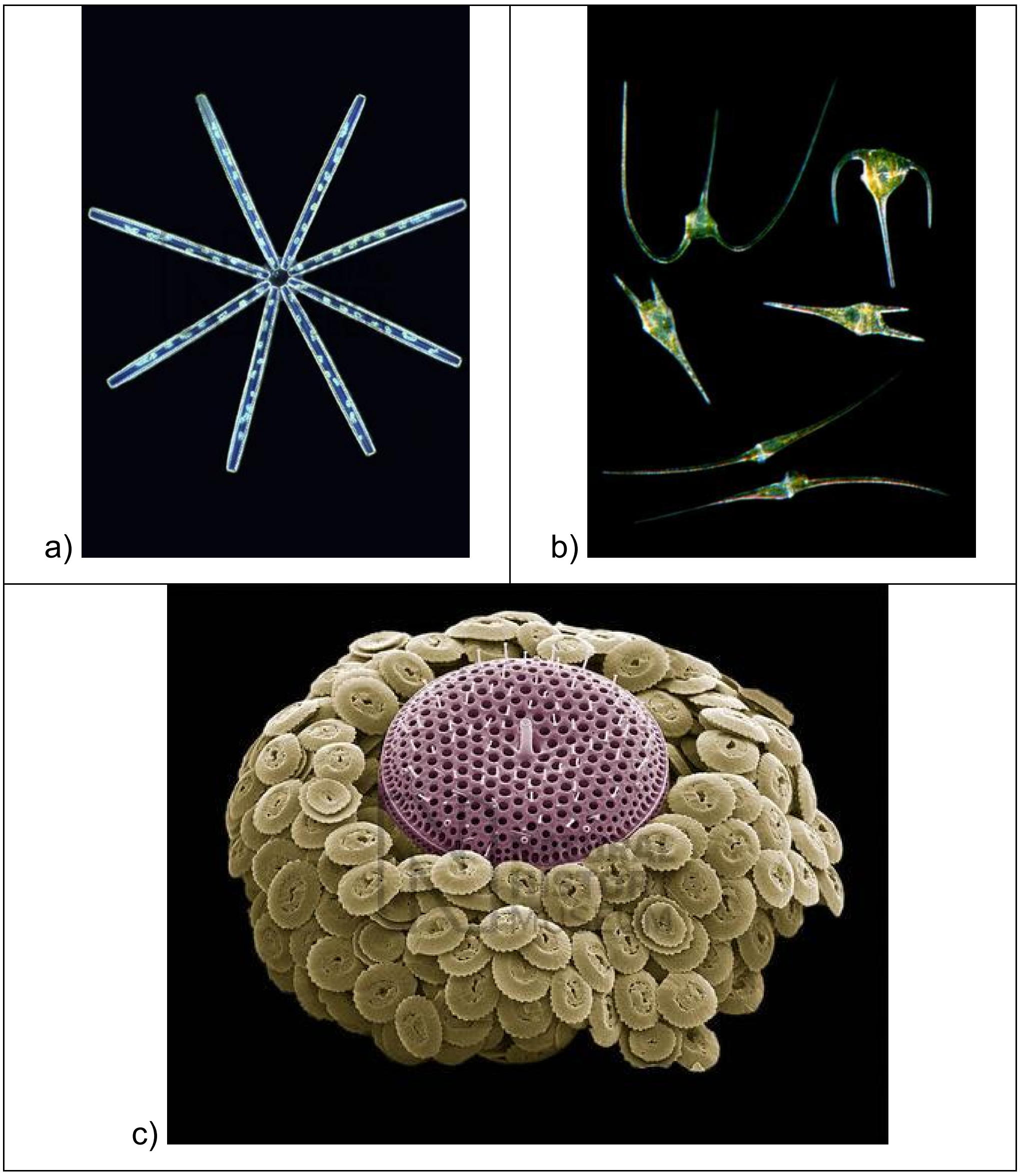


Figure 1.3 Examples of Diatoms (a), Dinoflagellates (b) and Coccolithophores (c) (URL 6).

1.2.1 LIMITING FACTORS IN PRIMARY PRODUCTIVITY

Nutrient availability and light are the major factors limiting primary productivity in the aquatic environment.

1- Nutrient Availability:

Primary producers use the dissolved nutrients (nitrate, phosphate, iron and silicate) to construct organic molecules. The abundance of these nutrients depends on their usage in biological processes. As the phytoplankton begin to grow, these nutrients become depleted in the surface waters and those species which have not been consumed by zooplankton and degraded by bacteria sink to the bottom resulting in a decline of primary productivity in the upper portion of the water column (Garrison, 2005).

Upwelling and vertical mixing play a very important role in returning these nutrients to the surface waters. In upwelling process, wind stress causes dense, cooler, and nutrient-rich waters move towards the surface, replacing the warmer and nutrient-depleted surface water. It has been shown that under the right divergent conditions, cool, nutrient-rich waters can also upwell from deeper waters to act as a seed for the formation of a cold-core eddy (URL 7). Besiktepe *et al.* (1994) has shown that there are 3 major eddies in the Sea of Marmara. Since prevailing winds in this region are mostly from North-East (Turkish Meteorological Office), thus not amenable to upwelling, the enrichment of nutrients in the surface water are caused by eddies rather than coastal upwelling.

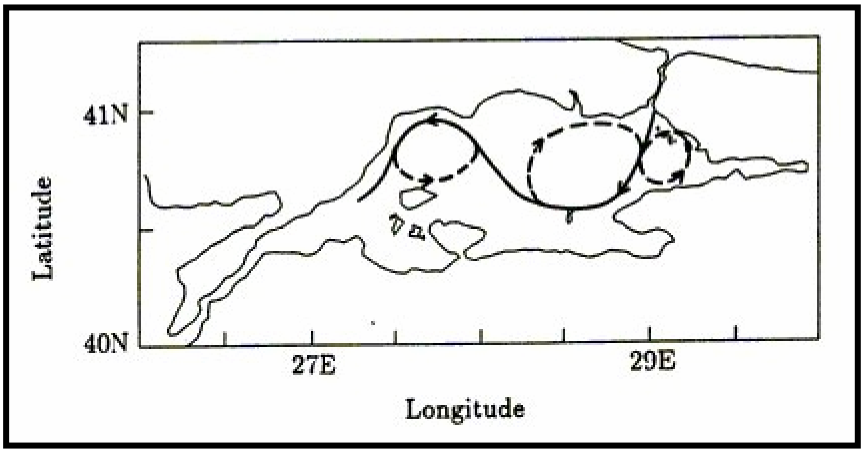


Figure 1.4 Eddy Formation in the Sea of Marmara
(Besiktepe *et al.*, 1994).

2- Light Availability:

Photosynthesis depends on quantity and quality of the light. Green light is reflected by the phytoplankton while red and infrared wavelengths are absorbed and converted to heat. Since red light can only penetrate to 3 meters below the surface, the highest primary production occurs in the upper portion of the euphotic zone. To the best of our knowledge, there is no photosynthetic activity occurring below 268 m (Garrison, 2005).

1.2.2 TEMPORAL AND SPATIAL VARIATIONS OF PRIMARY PRODUCTIVITY

According to Cloern (1996) phytoplankton blooms exhibit 3 major characteristics: (1) recurrent seasonal events that usually persist (2) aperiodic events that often over periods of weeks, persist for periods of days and (3) exceptional events that are typically dominated by few species some of which as we have indicated above some times can be toxic.

A common annual cycle begins with large winter-spring diatom blooms followed by summer blooms of small flagellates, dinoflagellates, and diatoms and then autumn blooms dominated by dinoflagellates (Garrison, 2005).

On a global scale primary productivity shows significant temporal and spatial variations. As can be seen in Figure 1.5, in Tropics, seasonal fluctuation of primary productivity is low, rarely exceeding 30 $gC/m^2/yr$. Although previous studies attributed this deficiency in productivity to low nutrient availability, recent studies have shown that insufficient amount of iron is the main cause (Bigg *et al.*, 2003; Blain *et al.*, 2007).

In six open ocean regions, although there have been high amount of dissolved nutrients and light availability, photosynthesis is very limited. These “high-nutrient, low-chlorophyll a” (HNLC) zones are found in the Eastern Equatorial Pacific, the Northwest Pacific, the Northeast Pacific, the Northeastern Subarctic Pacific, the Western Subarctic Pacific and the Southern Ocean. Iron has been defined as the physiological limitation factor as the cause of the high-nitrate, low-chlorophyll phenomenon (Rosen and Duffy, 2007).

The application of iron fertilization in the HNLC zones leads to increase phytoplankton biomass and photosynthesis rate in the surface waters (Behrenfeld *et al.,* 1996; Boyd *et al.*, 2000).

In high northern latitudes, light availability allows primary productivity only in summer with values less than 25 $gC/m^2/yr$.

Temperate and southern subpolar regions have the highest primary productivity reaching an average of 120 $gC/m^2/yr$. Moderate amount of light and nutrient make the ideal conditions for phytoplankton growth (Garrison, 2005).

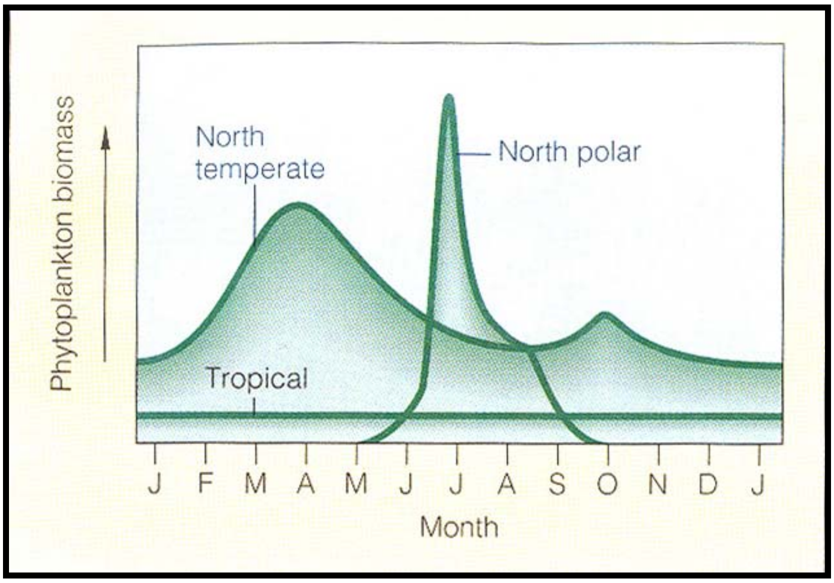


Figure 1.5 Variation in the biomass of phytoplankton by season and latitude (Garrison, 2005).

As well as physical factors, biological factors control phytoplankton abundance in the ocean (Figure 1.6). In late spring, enormous increase in the number of grazers causes a sudden decline in phytoplankton abundance although all physical conditions are available for phytoplankton proliferation (Stowe, 1996).

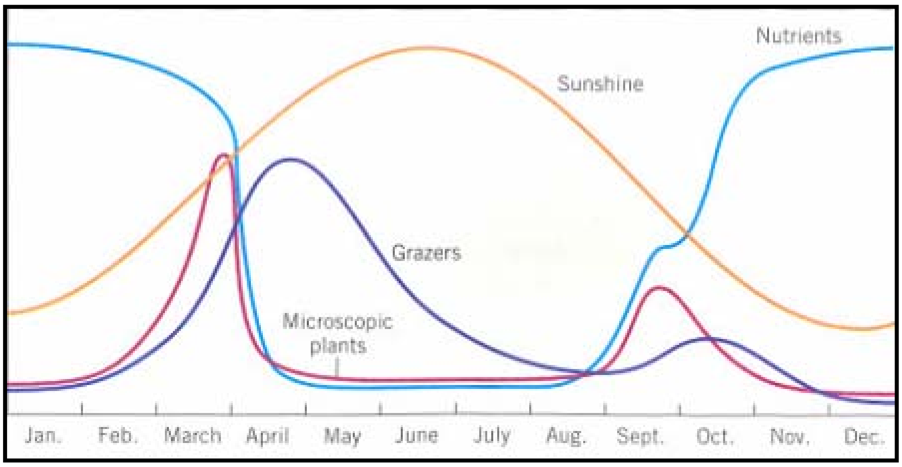


Figure 1.6 Typical Seasonal Variations in the Abundance of Sunlight, Nutrients, Microscopic Plants, and Grazers in Surface Waters at Temperate Latitudes (Stowe, 1996).

CHAPTER 2

MATERIALS AND METHODS

Of particular interest to our study is the 400-700 nm section of the electromagnetic spectrum, called Photosynthetically Active Radiation (PAR). PAR is used to calculate the chlorophyll a content of the sampling area (Figure 2.1 and 2.2).

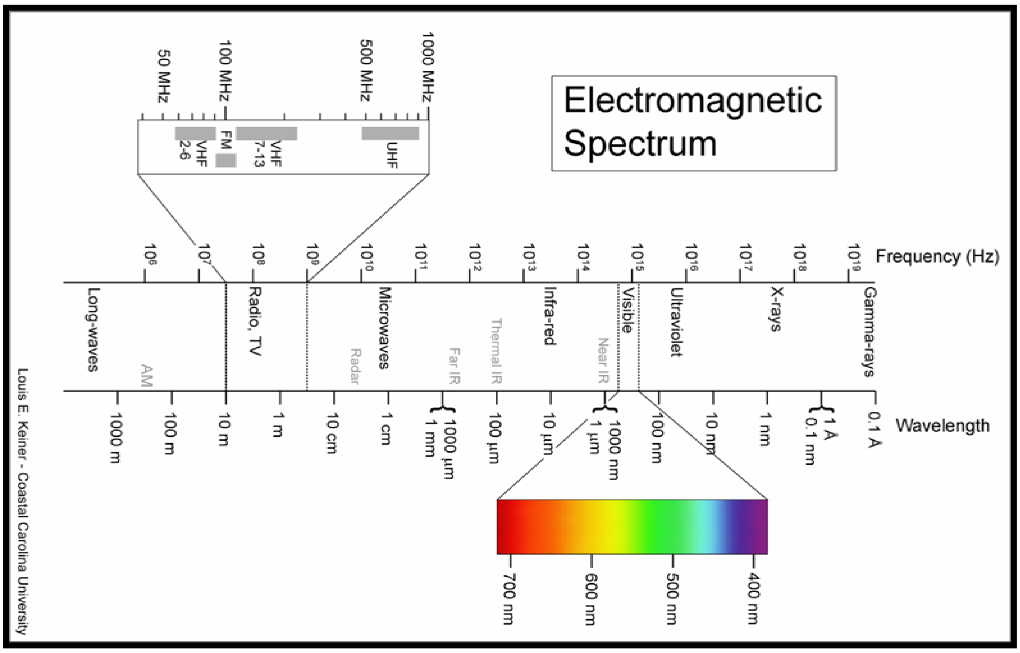


Figure 2.1 Electromagnetic Spectrum (URL 8).

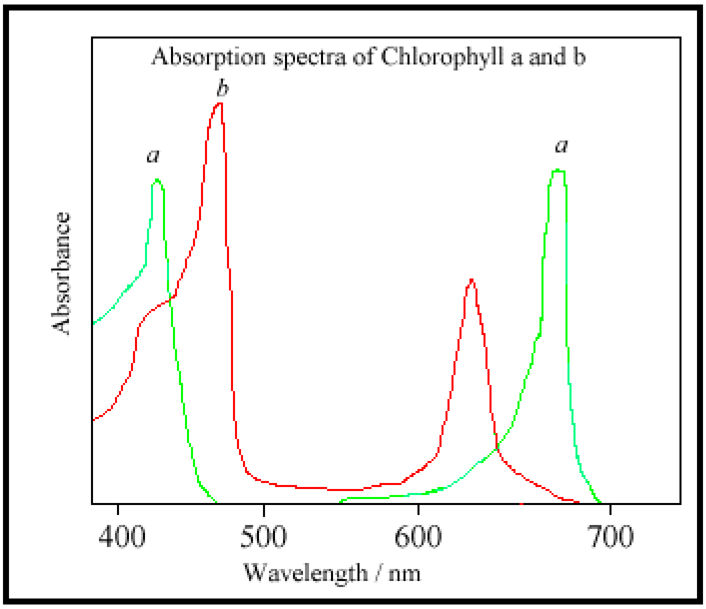


Figure 2.2 Absorption Spectra of Chlorophyll a and b (URL 9).

2.1 SAMPLING

SeaWiFS and MODIS-Aqua are two of the sensors which can be used to calculate the amount of chlorophyll content of the sea surface. This data can freely be acquired from The Ocean Biology Processing Group (OBPG) which administers the data recorded by both sensors. The spatial resolution of SeaWiFS data is 9x9 kilometers and that of MODIS-Aqua is 4X4 kilometers. In our study, we have utilized data recorded by both sensors to evaluate chlorophyll dynamics and the effect of climatic change.

SeaWiFS is a scanning radiometer collecting data since August 1997 through 8 spectral bands, whereas MODIS-Aqua is a scanning radiometer collecting data since June 2002 with 36 spectral bands.

The major characteristics of MODIS and SeaWiFS spectral bands are given in Table 2.1.

Table 2.1 MODIS-Aqua and SeaWiFS spectral bands used in ocean color processing (Franz *et al.*, 2005).

MODIS Band	SeaWiFS Band	MODIS Wavelength	SeaWiFS Wavelength
8	1	412	412
9	2	443	443
10	3	488	490
11	4	531	510
12	5	551	555
13	6	667	670
15	7	748	765
16	8	869	865

Radiances in bands 15 and 16 are used to evaluate atmospheric contribution of observed radiance. The red band (670 nm) is used to make corrections for NIR radiance leaving the ocean. These calculations are necessary to remove the atmospheric noise from chlorophyll radiance so that water-leaving radiance (Lw) can be obtained. Thus the effects of solar illumination, viewing geometry and atmospheric attenuation losses are corrected by using normalized Lw (Franz *et al.*, 2005).

The consistency and accuracy of MODIS and SeaWiFS data acquired by Ocean Biology Discipline Processing Group (OBPG) is very high. As indicated by Franz (2005), assessment of quality of the data is maintained by comparison with *in-situ* observations, sensor-to-sensor temporal comparisons, latitudinal trend comparisons, cross-scan and detector dependent residuals.

It must be added that a large number of *in-situ* measurements contributed by 43 institutions to SeaBASS which provides the necessary in-situ information for the statistical validation of satellite products (Figure 2.3). This cooperation has enabled researchers to construct better algorithms so that the chlorophyll a content can be calculated with utmost accuracy (Werdell and Bailey, 2002).

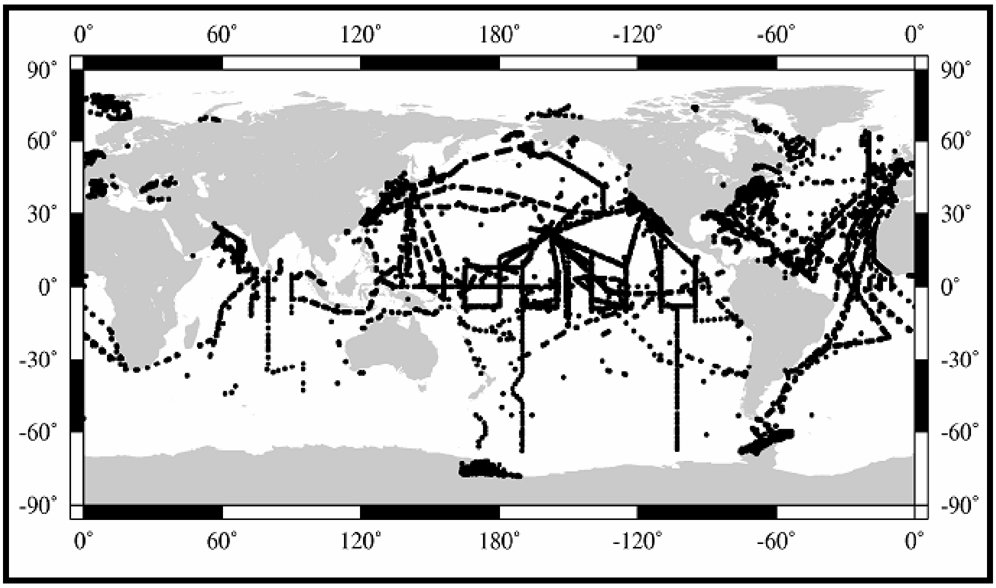


Figure 2.3 A map of all data points in the SeaBASS bio-optical data set (Werdell and Bailey, 2002).

For the chlorophyll estimation, over 220,000 phytoplankton pigment concentrations are collected by these institutions (Figure 2.4).

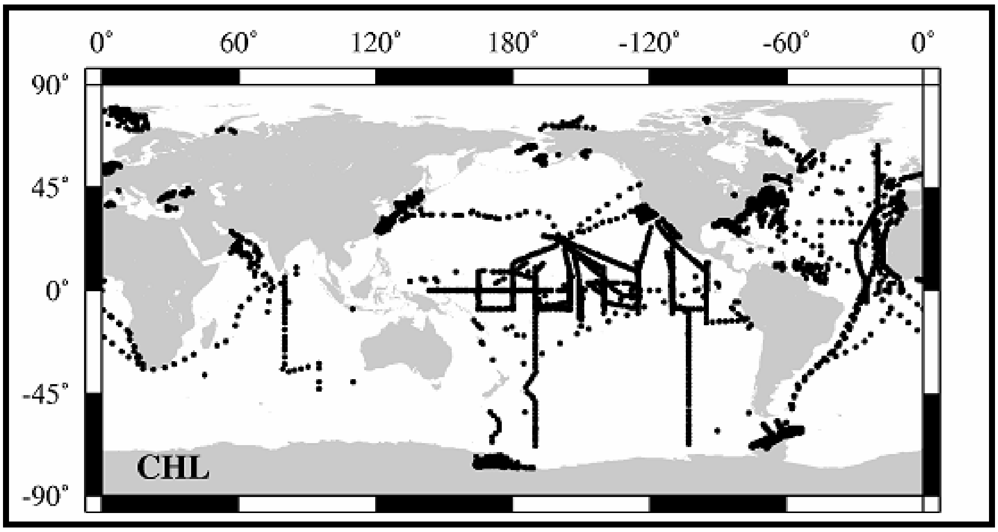


Figure 2.4 Maps of the distributions of chlorophyll a concentrations (CHL) (Werdell and Bailey, 2002).

According to validation results of SeaWiFS and MODIS-Aqua acquired by using in-situ match-ups (Figure 2.5 and 2.6), r^2 for the regressions are about 0.8 for each sensor (Bailey *et al.*, 2006; URL 10).

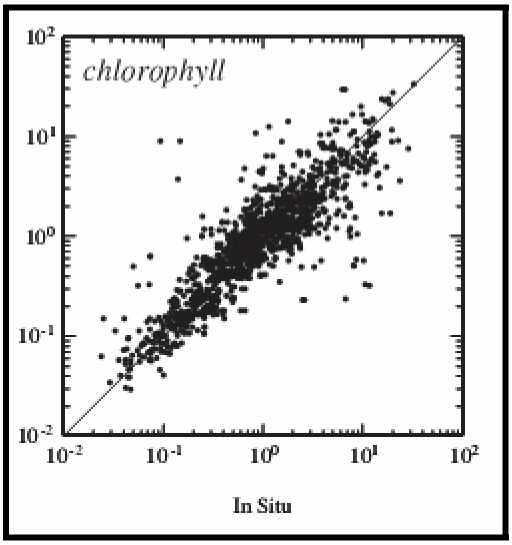


Figure 2.5 *In situ* and SeaWiFS data set comparison (Bailey *et al.*, 2006).

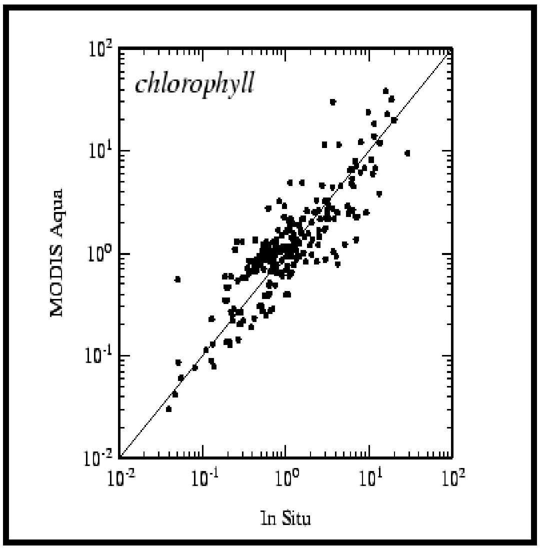


Figure 2.6 *In situ* and MODIS-Aqua data set comparison (URL 10).

Marine Optical Buoy (MOBY) is another important data source for calibrating these two sensors (Herring, 1994). The purpose of MOBY's mission is to detect penetrating and reflecting visible and near-infrared radiation from the ocean. These measurements are helpful to obtain time series databases for bio-optical algorithms such as chlorophyll amount.

As a result of these various techniques and data analysis a visual representation of chlorophyll a content for a particular location can be obtained from OBPG. An example of such a map, which is also the area of our study, is shown in Figure 2.7.

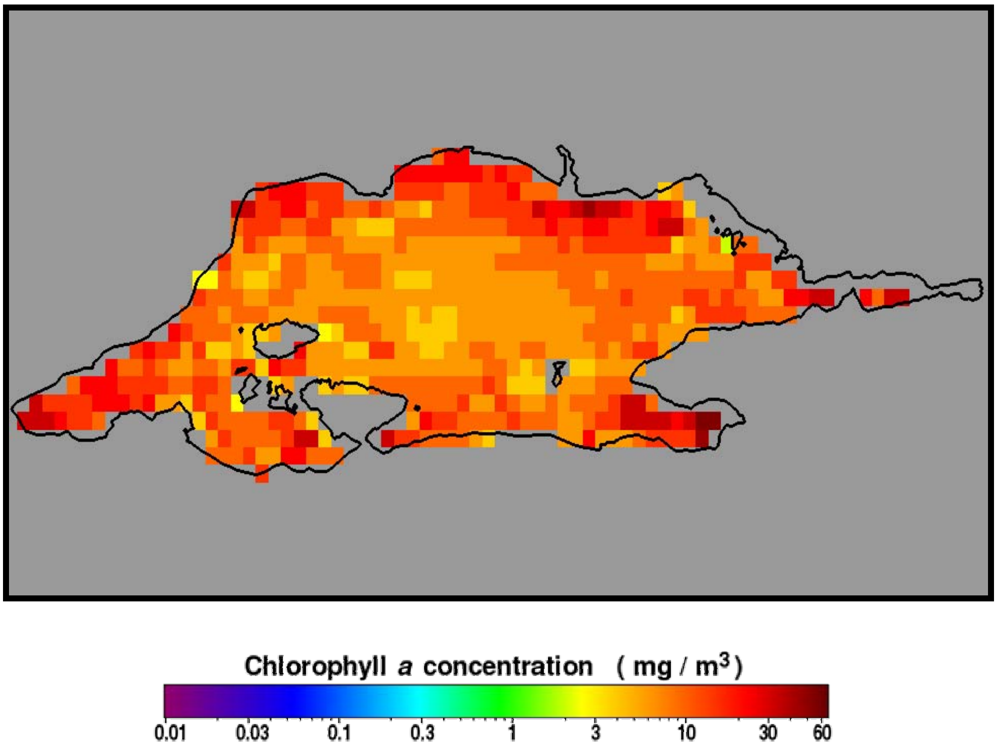


Figure 2.7 Chlorophyll a concentrations for the month of April, 2003 calculated from images taken by MODIS-Aqua.

2.2 DATA ANALYSIS

Records of in situ measurements of sea surface temperature (SST) data at the Turkish Meteorological Office are limited and some of it is not of sufficient length for analyzing climatic fluctuations with the exception of Tekirdağ Weather Station which we have used in this study.

The remote sensing data which used in this study were recorded by SeaWiFS and MODIS-Aqua sensors and have been downloaded from the website of Ocean Biology Discipline Processing Group (OBPG) (http://oceancolor.gsfc.nasa.gov/) (The acquisition of this data is free and available to those who are interested). 44 sampling sites for MODIS-Aqua and 60 sampling sites for SeaWiFS have been selected for detailed analysis (Figure 2.8 and 2.9).

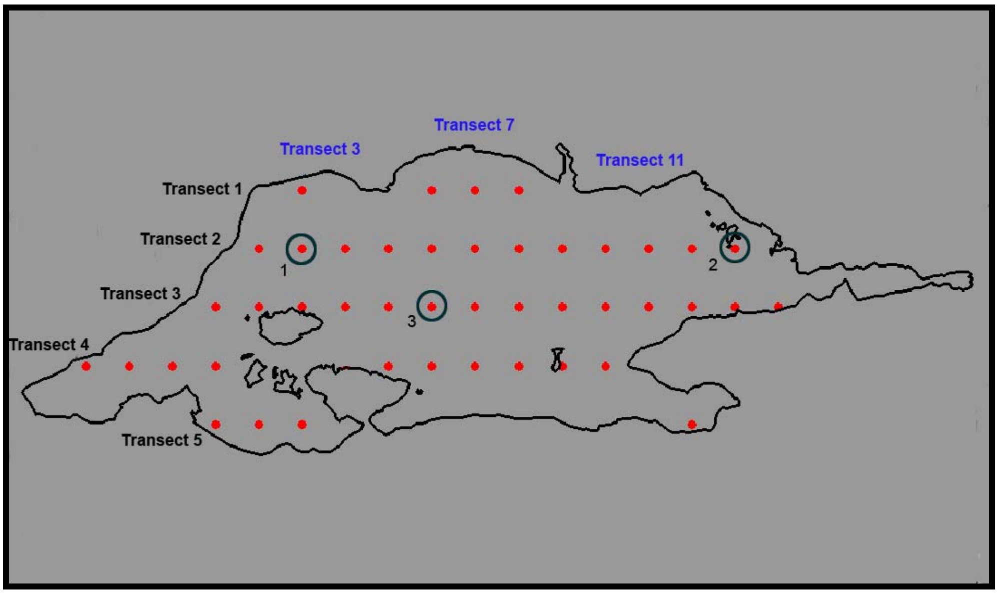


Figure 2.8 44 Sampling Stations for MODIS-Aqua (Circled locations used for SeaWiFS and MODIS-Aqua comparison).

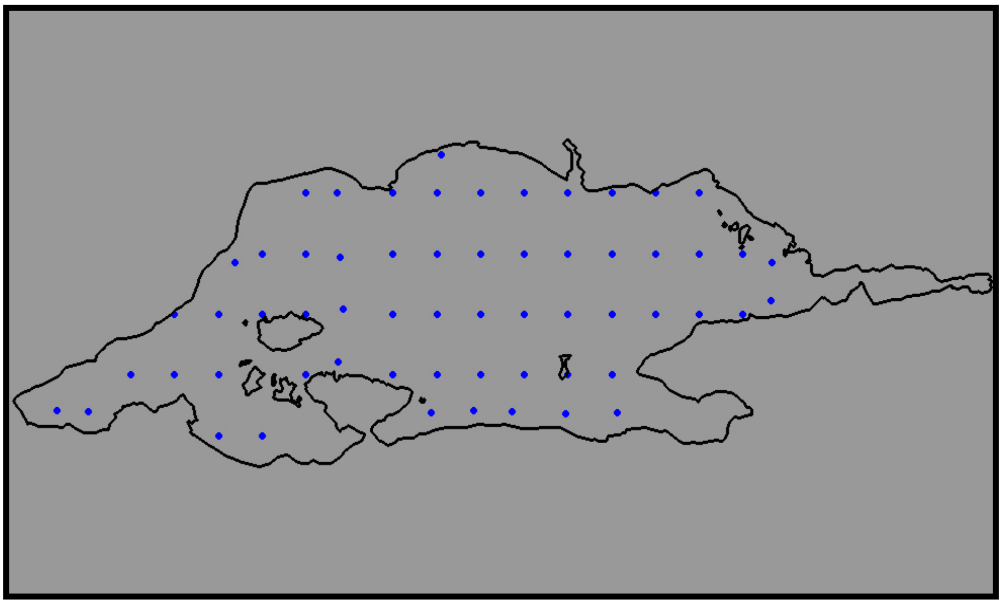


Figure 2.9 60 Sampling Stations for SeaWiFS.

For data processing and analysis we have used TNT mips 6.9, an integrated Geographical Information System (GIS) and Remote Sensing software ideally suited to handle large amounts of data.

As recommended by OBPG we have used the following equations to calculate chlorophyll concentrations and SST:

Chlor_a= 10** ((0.015*pixel value) -2) for the MODIS-Aqua chlorophyll data set,

SST= ((0.000717*pixel value)-2) for the MODIS-Aqua SST data set and

Chlor_a= 10** ((0.000058*pixel value)-2) for SeaWiFS chlorophyll data sets.

Where: Chlor_a: Chlorophyll Concentration in mg/m^3

SST: Sea Surface Temperature in ºC.

Sancak *et al.* (2005) in a study lasting about a year involving the Black Sea, Mediterranean and the Sea of Marmara reported that at low concentrations some of the algorithms used for calculating chlorophyll a content was not in complete agreement with in situ measurements. Sancak *et al.* evaluated data taken by only SeaWiFS. As we have stated earlier our analysis are based on data taken both by SeaWiFS and MODIS-Aqua sensors. The remarkable similarities between the data taken by both sensors, based on monthly averages clearly indicate that our calculations are based on data which are representative of the actual chlorophyll content (Figure 3.1). Perhaps for analyses based on shorter time periods improvements suggested by Sancak *et al.* (2005) are valid and should be incorporated in such studies.

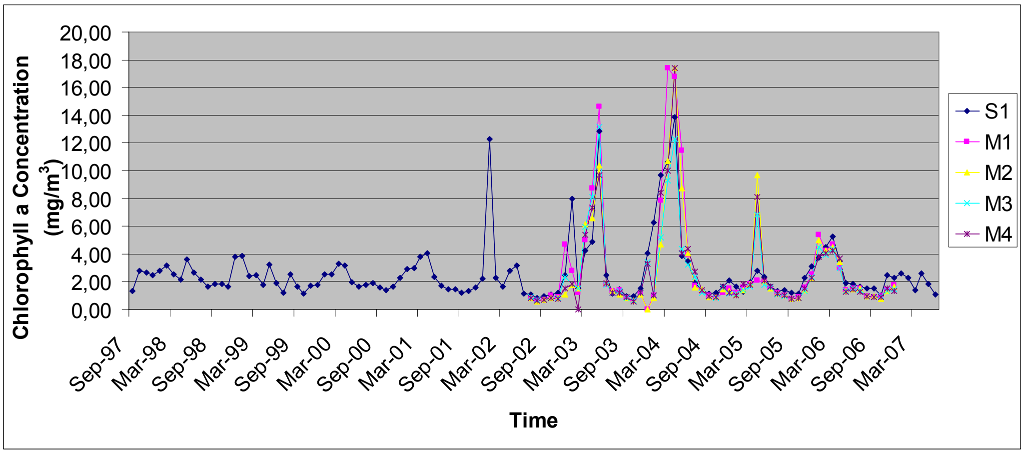
CHAPTER 3

RESULTS AND DISCUSSION

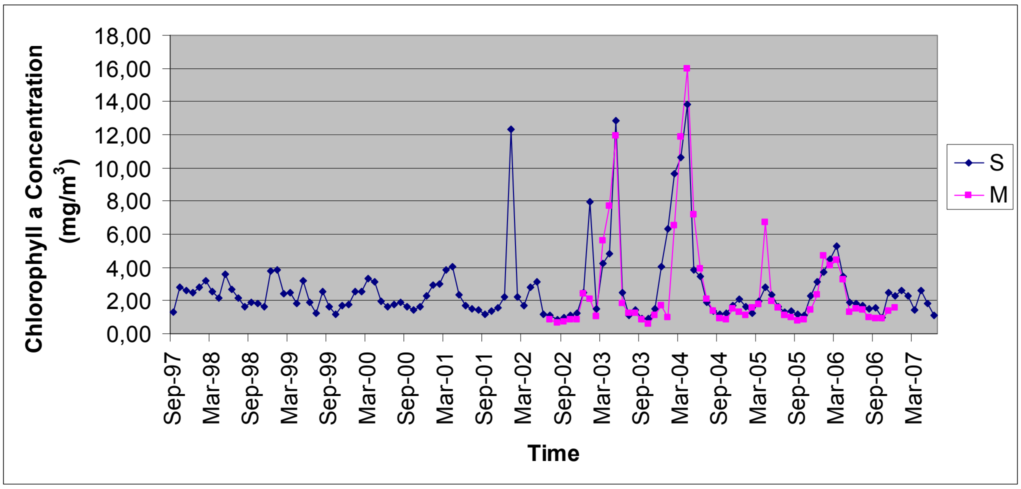
In order to assess the effects of climatic change a data set spanning over several years is needed. Thus SeaWiFS set recorded during 1997- 2007 period is better suited for this type of analysis than MODIS-Aqua data which covers a shorter period of 2002-2006. However, it must be remembered that the spatial resolution of MODIS-Aqua sensor is approximately 4 times better than those recorded by SeaWiFS sensor. However a correlation analysis between the two data sets obtained at three stations (Figure 2.8) during 2002-2006 period is significantly correlated indicating that at least when monthly averages are concerned either data set can be used in place of the other. We consider this result as one of the most importing finding in our study because of its possible applications in other studies related to climate change. For studies requiring finer resolution, which are too numerous to list here, MODIS-Aqua sensor data should naturally be preferred.

In a sense these high correlations also verify the validity of several algorithms developed by OBPG since both data sets has been recorded by two independent sensors (Figure 3.1).

a) 1.Station:

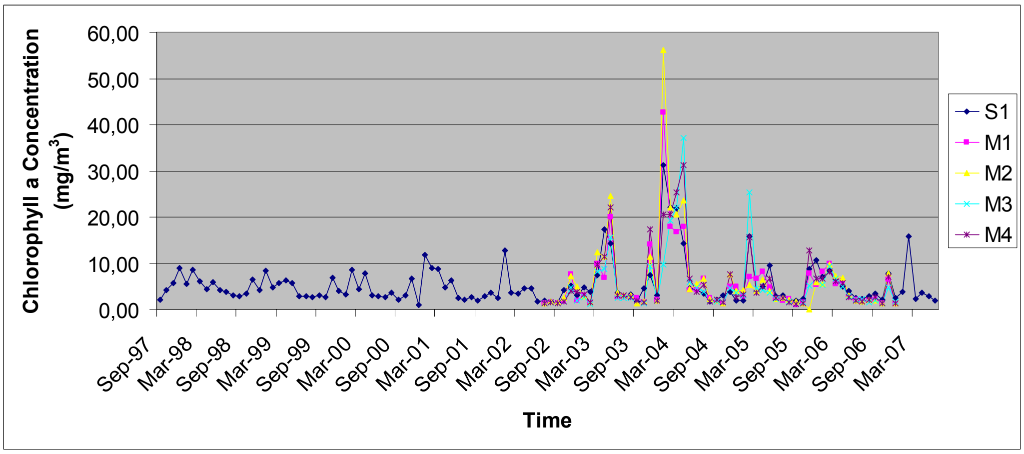


Chlorophyll a Concentration (mg/m3)
20,00
18,00
16,00
14,00
12,00
10,00
8,00
6,00
4,00
2,00
0,00
Sep-97
Mar-98
Sep-98
Mar-99
Sep-99
Mar-00
Sep-00
Mar-01
Sep-01
Mar-02
Sep-02
Mar-03
Sep-03
Mar-04
Sep-04
Mar-05
Sep-05
Mar-06
Sep-06
Mar-07
Time
S1
M1
M2
M3
M4

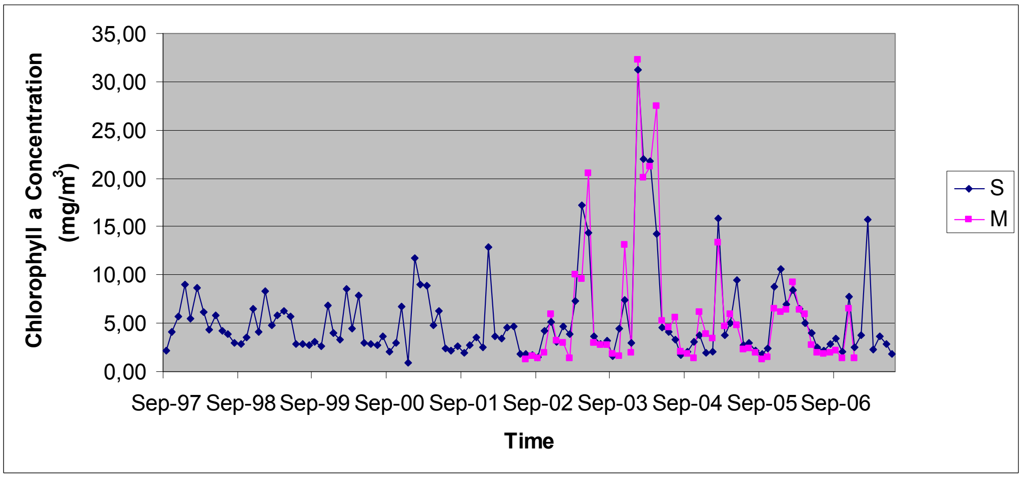


Chlorophyll a Concentration (mg/m3)
18,00
16,00
14,00
12,00
10,00
8,00
6,00
4,00
2,00
0,00
Sep-97
Mar-98
Sep-98
Mar-99
Sep-99
Mar-00
Sep-00
Mar-01
Sep-01
Mar-02
Sep-02
Mar-03
Sep-03
Mar-04
Sep-04
Mar-05
Sep-05
Mar-06
Sep-06
Mar-07
Time
S
M

b) 2.Station:

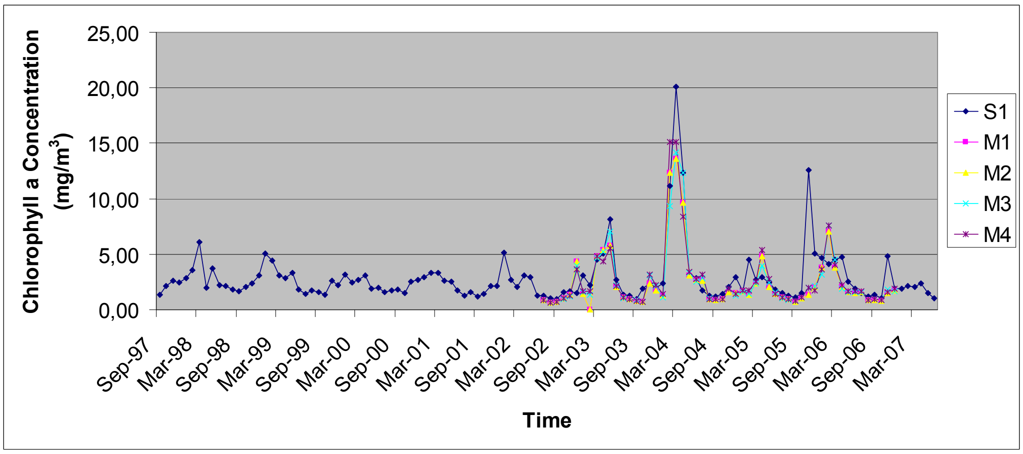


Chlorophyll a Concentration (mg/m^3)
60,00
50,00
40,00
30,00
20,00
10,00
0,00
Sep-97
Mar-98
Sep-98
Mar-99
Sep-99
Mar-00
Sep-00
Mar-01
Sep-01
Mar-02
Sep-02
Mar-03
Sep-03
Mar-04
Sep-04
Mar-05
Sep-05
Mar-06
Sep-06
Mar-07
Time
S1
M1
M2
M3
M4



Chlorophyll a Concentration (mg/m^3)
35,00
30,00
25,00
20,00
15,00
10,00
5,00
0,00
Sep-97 Sep-98 Sep-99 Sep-00 Sep-01 Sep-02 Sep-03 Sep-04 Sep-05 Sep-06
Time
S
M

c) 3.Station:



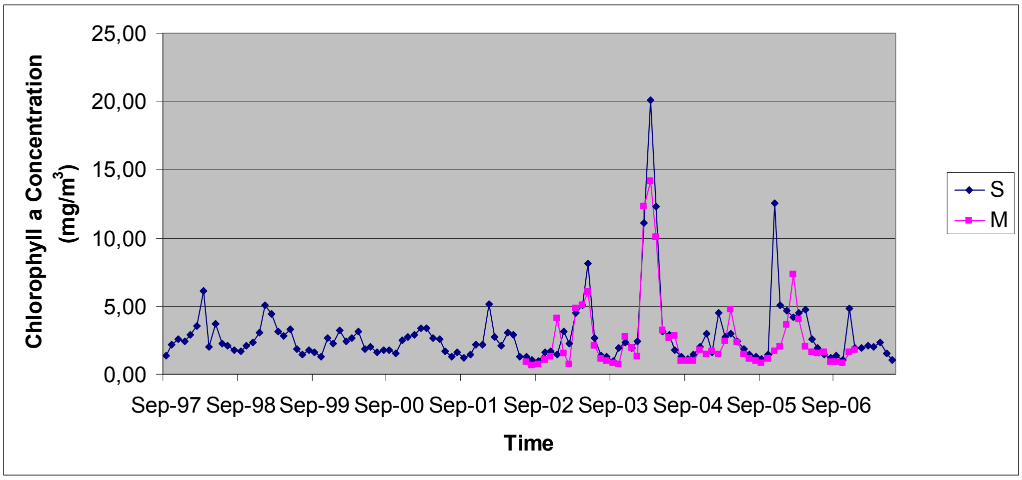


Figure 3.1 Chlorophyll a contents of 3 stations calculated by using SeaWiFS and MODIS-Aqua data sets. Correlation coefficients (r) between SeaWiFS and MODIS-Aqua for each stations are 0.87 (a), 0.83 (b) and 0.91 (c). The results are statistically significant at 1% level.

(S and S1: Chlorophyll a contents of SeaWiFS sampling station; M1, M2, M3 and M4: Average Chlorophyll a contents of MODIS-Aqua sampling stations)

3.1 PATTERNS OF MONTHLY CHOLOROPHYLL A FLUCTUATIONS

An example of spatial distribution of chlorophyll a, which is highly representative of the general spatial pattern in the Sea of Marmara, is shown in Figure 2.7. Chlorophyll a values are generally higher near the coastal as compared to off shore locations. Also there is a general pattern showing that chlorophyll a measurements at eastern locations are higher than those measured at the western portion of the sea (For exceptions please see below).

We have plotted the chlorophyll value of each pixel of the entire data set to ascertain the general patterns of month to month changes of chlorophyll a content and identify those locations at which significant deviations from these patterns do occur (Figure 3.2 and 3.3). As can be seen between the data sets obtained by the two sensors there are remarkable similarities. Majority of the blooms occurs during the winter and spring seasons followed by a smaller secondary bloom during the fall season which are characteristic of temperate regions. It must be noted that there are also several measurements which significantly deviate from the general patterns. As can be seen in Figure 3.3, the majority of these anomalous blooms at the Eastern part where the region is heavily polluted [For a detailed analysis of the effects of pollution on phytoplankton species in Izmit Bay, see Aktan *et al.* (2005)]. As was explained earlier upwelling and vertical mixing which, along with nutrient input content, are the principle causative mechanism for phytoplankton blooms along the coastal regions. A more plausible explanation is that since most of the polluted regions are located near these stations nutrients associated with polluted water are probably the reason for the observed chlorophyll a increase.

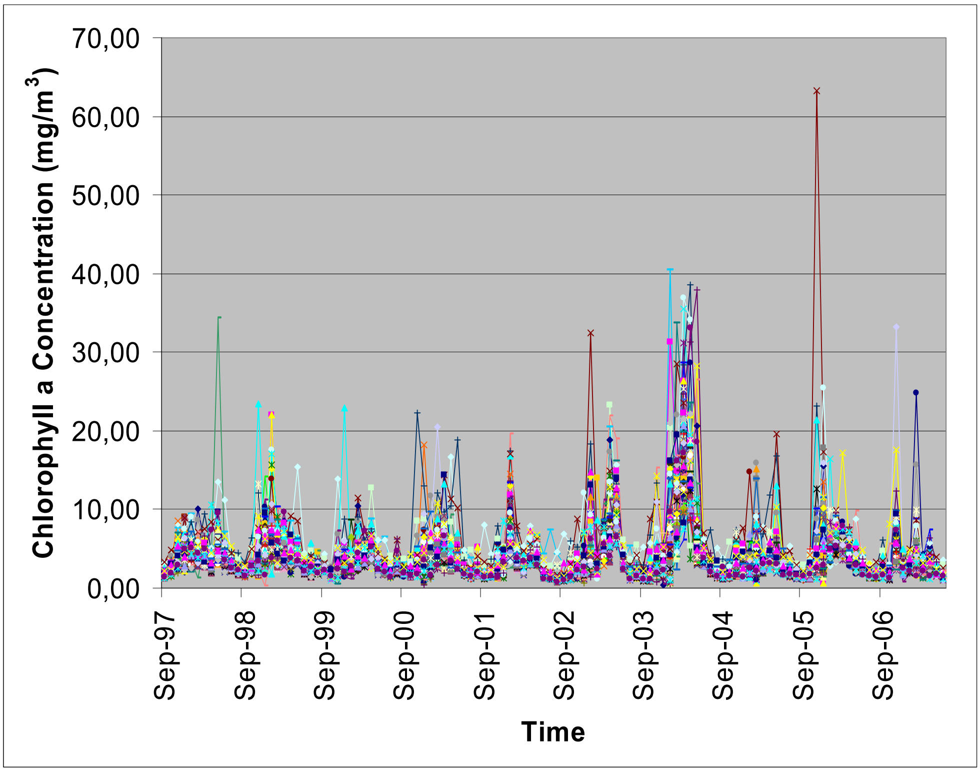


Figure 3.2 SeaWiFS Data Set.

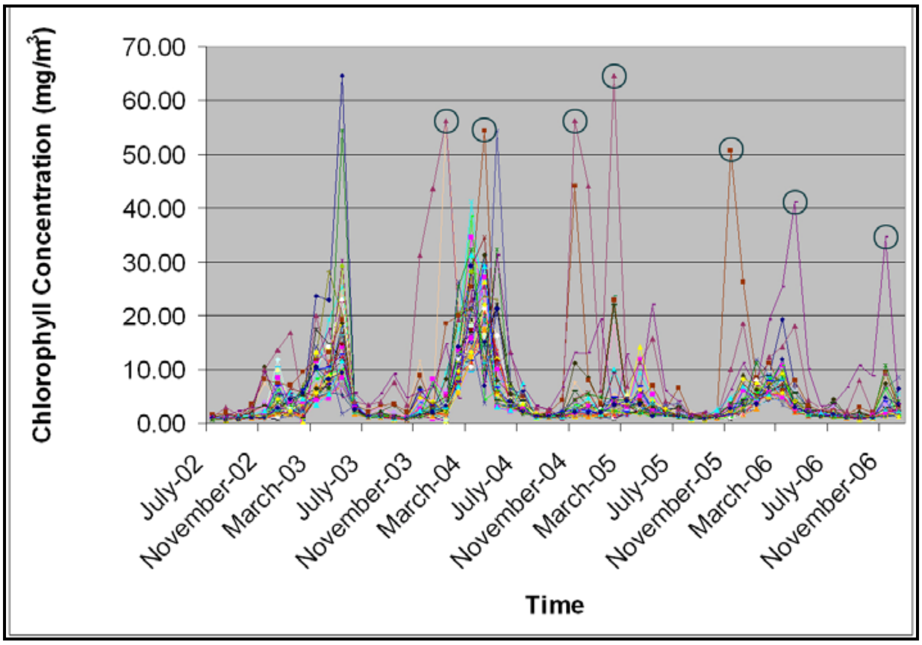


Figure 3.3 MODIS-Aqua Data Set (Circled stations are located in the Eastern part of the Sea of Marmara).

Despite anomalous increases at some locations, temporal variations based on monthly averages of all avail pixels (60 belonging to SeaWiFS and 44 to MODIS-Aqua) are remarkably uniform and well defined (Figure 3.4). Similar analysis using MODIS-Aqua data calculated along East-West and North-South transects and related correlation coefficients (r) verify this finding (Figures 3.5 and 3.6, Tables 3.1 and 3.2).

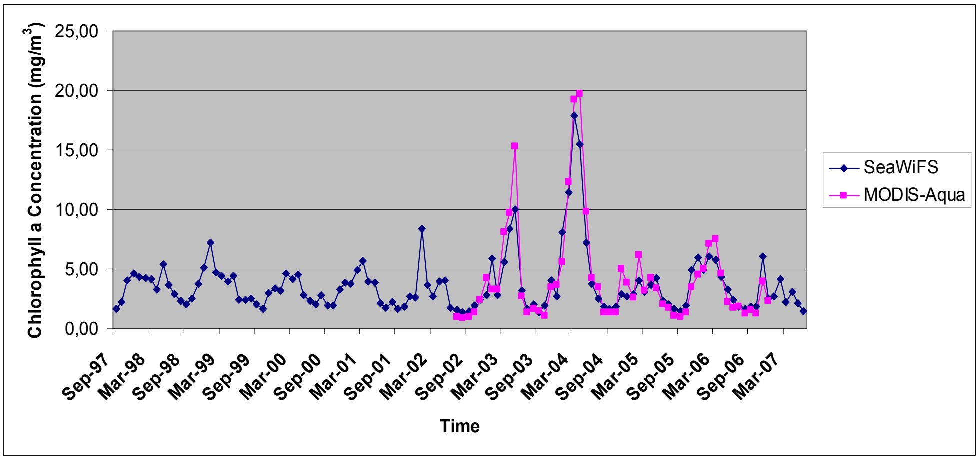


Figure 3.4 Time Series of Monthly Averages of Chlorophyll a Concentrations during 1997-2007 based on SeaWiFS and MODIS-Aqua data sets.

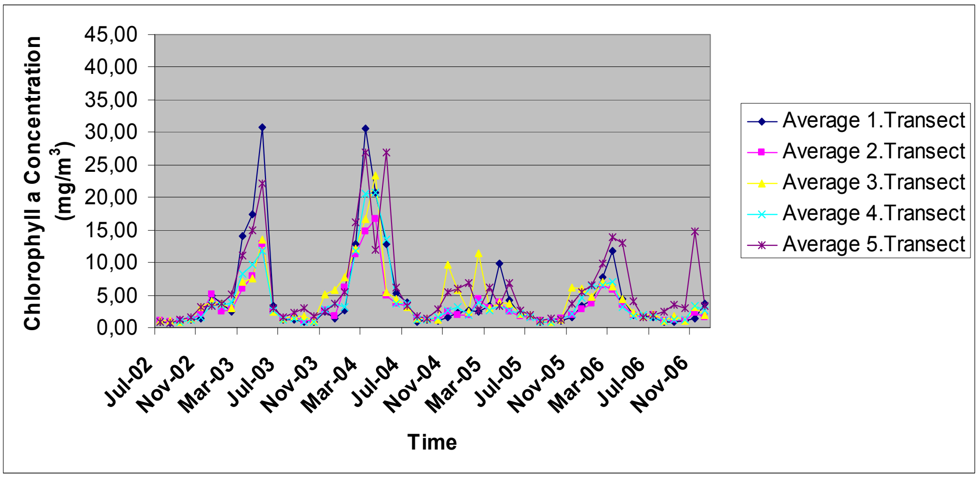


Figure 3.5 Averaged Chlorophyll a Concentration of Each Transect along East-West Direction.

Table 3.1 Pearson Coefficients (r) between chlorophyll a values measured at East-West Transects. (For locations see Figure 2.8) Correlation coefficients among all transects are significant at 1% level.

	2. Transect	3. Transect	4. Transect	5. Transect
1. Transect	0.91	0.78	0.90	0.84
2. Transect		0.92	0.94	0.76
3. Transect			0.87	0.65
4. Transect				0.84

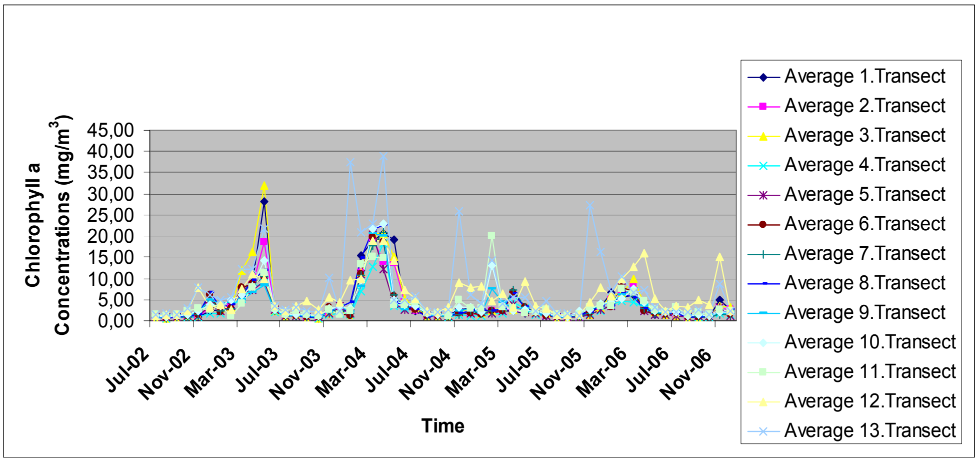


Figure 3.6 Averaged Chlorophyll a Concentration of Each Transect along North-South Direction.

Table 3.2 Pearson Coefficients (r) between chlorophyll a values measured at North- South Transects.

(For locations see Figure 2.8) Correlation coefficients among all transects are significant at 1% level.

(Tran: Transect)

	1. Tran.	2. Tran.	3. Tran.	4. Tran.	5. Tran.	6. Tran.	7. Tran.	8. Tran.	9. Tran.	10. Tran.	11. Tran.	12. Tran.
2. Tran.	0.97											
3. Tran.	0.96	0.96										
4. Tran.	0.83	0.85	0.85									
5. Tran.	0.81	0.90	0.82	0.89								
6. Tran.	0.83	0.90	0.84	0.95	0.96							
7. Tran.	0.84	0.88	0.84	0.98	0.93	0.99						
8. Tran.	0.82	0.87	0.82	0.96	0.94	0.98	0.98					
9. Tran.	0.75	0.82	0.77	0.93	0.92	0.94	0.94	0.94				
10. Tran.	0.81	0.85	0.82	0.92	0.88	0.91	0.91	0.91	0.97			
11. Tran.	0.67	0.70	0.67	0.72	0.73	0.74	0.74	0.75	0.82	0.89		
12. Tran.	0.68	0.71	0.67	0.71	0.71	0.71	0.71	0.69	0.70	0.69	0.58	
13. Tran.	0.57	0.54	0.53	0.64	0.57	0.61	0.63	0.66	0.63	0.67	0.61	0.61

Based on these findings we can now calculate the average values of chlorophyll a for each month (Figure 3.7). The fact that the majority of phytoplankton productivity occurs during the Spring season which includes the months of February, March and April and a lesser secondary bloom during November are similar to findings at other temperate regions, for example California coast (Tont, 1981); however, the considerable production activity in the Sea of Marmara during the month of January and December is, to the best of our knowledge, is most unusual. A likely explanation is the increase in the amount of discharge of water contaminated with nutrients originating on land.

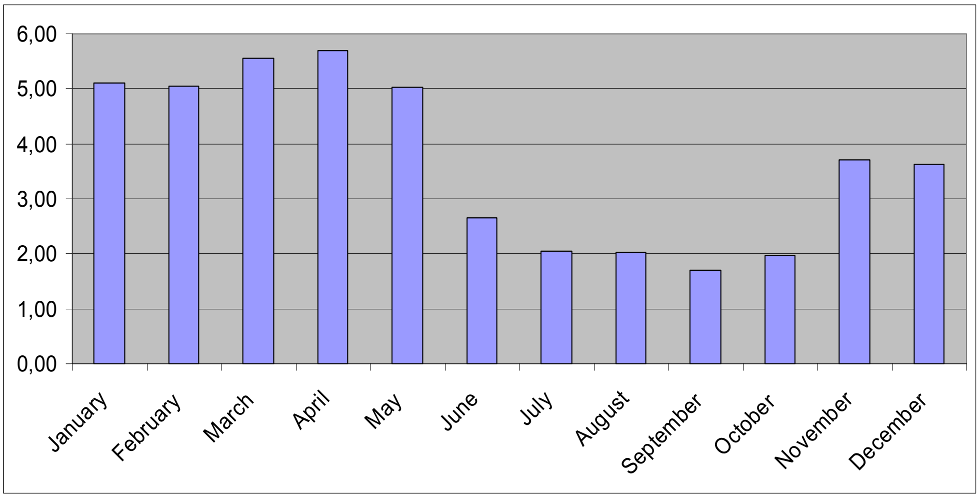


Figure 3.7 Monthly Cycles of Chlorophyll a Concentration (mg/m^3) in the Sea of Marmara based on SeaWiFS data set (Each bar represents average of all values belonging to that particular month, during 1997-2007).

3.2 SST and CHLOROPHYLL a CORRELATIONS

In a recent paper by Gregg *et al.* (2003) it was reported that globally, since 1980'es there has been 6% decrease in annual marine primary production and they attribute this decrease to global warming. As can be easily seen in several graphs presented above we have not seen a similar decrease in primary productivity in the Sea of Marmara. Sea surface temperatures (SST) measured near Tekirdağ by Turkish Meteorological Office (1997-2007) and those recorded by MODIS-Aqua (2002-2006) do not show any significant increase in SST values (Figure 3.8). Since our study area is highly localized compared to Gregg *et al.*'s (2003) there might have been mitigating circumstances, such as local discharges, offsetting the effects of global warming.

However, as has been discussed in Chapter 1, even though temperature change itself may not effect primary production directly it may be indicative of other processes such as upwelling and vertical mixing. Lowering of SST in the sea has been recognized as a signature of upwelling and vertical mixing since during this process the warm surface waters are replaced by the colder subsurface waters. Indeed, correlations between monthly averages of SST and corresponding chlorophyll a values are statistically significant (inverse) at 1% level where r= -0.53 and the equation of the fitted model is:

Chlorophyll a = 7.09199 – 0.215402* SST

(For details see Appendix A)

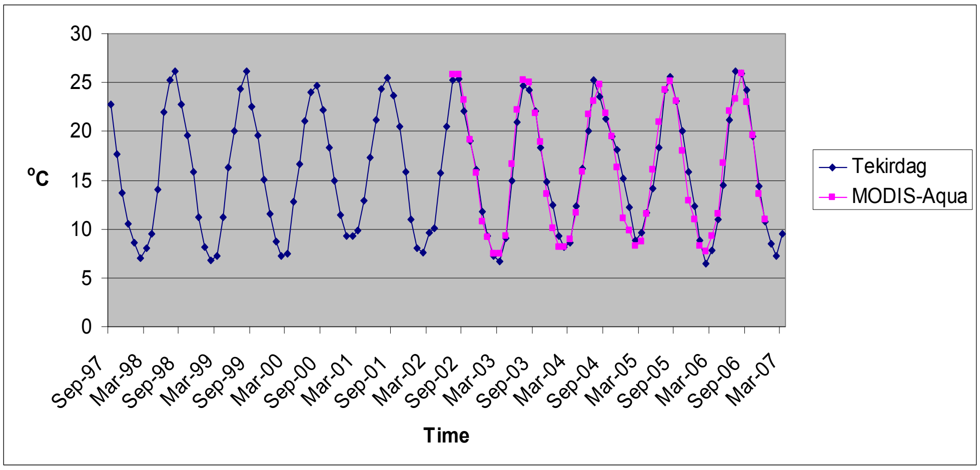


Figure 3.8 Sea Surface Temperature (SST) during 1997-2007.

CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE STUDIES

Our findings presented in this thesis in addition to their intrinsic scientific value will also have practical applications in both marine biology and remote sensing studies. The wealth of data we were fortunate to acquire enabled us to try a variety of techniques and calculations resulting in such applications. For example we have found that MODIS-Aqua and SeaWiFS chlorophyll data can be used interchangeably if the analysis is based on monthly averages. Similarly a few well chosen transects consisting of a handful of stations can be used as representative of the entire region. More importantly although Roden (1960) have shown that along southwestern region of the Pacific Ocean, monthly averages of SST show coherence for nearly 200 kilometers, still it was surprising for us to find out that in a much more complex location such as Marmara Sea, SST measurements taken at a single station (Tekirdağ) will be representative of the entire area and these values will be almost identical to those recorded by satellite sensors.

The fact that either SST or Chlorophyll a value can be approximated when one is unknown by using a fitted linear model which is statistically sound will again be of great use not only for basic research but for practical applications such as assessing the effects of pollutants at major discharge locations.

We believe a cross comparison of chlorophyll a values calculated by remote sensing techniques at several locations in Mediterranean, Aegean and Black Sea will be most interesting. Also, monitoring the major affluent discharge stations by using data taken at shorter time intervals and with more resolution can be very beneficial for evaluating the effects of pollution on primary production.

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APPENDIX A

Regression analysis between monthly averages of sea surface temperature (SST) and Chlorophyll a concentration is shown during 1997-2007 period. Chlorophyll values have been recorded by SeaWiFS. SST values are obtained from Tekirdağ Meteorological Station.

Coefficients

	Least Squares	*Standard*	*T*	
Parameter	*Estimate*	*Error*	*Statistic*	*P-Value*
Intercept	7.09199	0.546969	12.966	0.0000
Slope	-0.215402	0.0321747	-6.69477	0.0000

Analysis of Variance

Source	*Sum of Squares*	*Df*	*Mean Square*	*F-Ratio*	*P-Value*
Model	207.375	1	207.375	44.82	0.0000
Residual	522.835	113	4.62686		
Total (Corr.)	730.21	114			

Correlation Coefficient = -0.532911

R-squared = 28.3994 percent

R-squared (adjusted for d.f.) = 27.7658 percent

Standard Error of Est. = 2.15101

Mean absolute error = 1.23675

Durbin-Watson statistic = 0.722076 (P=0.0000)

Lag 1 residual autocorrelation = 0.630902

The output shows the results of fitting a linear model to describe the relationship between Chlorophyll a Concentration and SST. The equation of the fitted model is

Chlorophyll a Concentration = 7.09199 - 0.215402* SST

Since the P-value in the ANOVA table is less than 0.05, there is a statistically significant relationship between Chlorophyll a Concentration and SST at the 95.0% confidence level.

The R-Squared statistic indicates that the model as fitted explains 28.3994% of the variability in Chlorophyll a Concentration. The correlation coefficient equals -0.532911, indicating a moderately strong relationship between the variables. The standard error of the estimate shows the standard deviation of the residuals to be 2.15101.

Since the P-value is less than 0.05, there is an indication of possible serial correlation at the 95.0% confidence level.