Characterizing Surface Temperature and Clarity of Kuwait's Seawaters Using Remotely Sensed Measurements and GIS Analyses

By

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Abstract

Kuwait sea surface temperature (SST) and water clarity are important water characteristics that influence the entire Kuwait coastal ecosystem. The spatial and temporal distributions of these important water characteristics should be well understood to obtain a better knowledge about this productive coastal environment. The aim of this project was therefore to study the spatial and temporal distributions of: Kuwait SST using Moderate Resolution Imaging Spectroradiometer (MODIS) images collected from January 2003 to July 2007; and Kuwait Secchi Disk Depth (SDD), a water clarity measure, using Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and MODIS data collected from November 1998 to October 2004 and January 2003 to June 2007, respectively.

Kuwait SST was modeled based on the linear relationship between level 2 MODIS SST data and *in situ* SST data. MODIS SST images showed a significant relationship with *in situ* SST data (r^2= 0.98, n = 118, RMSE = 0.7 ^{o}C). Kuwait SST images derived from MODIS data exhibited three spatial patterns of Kuwait SST across the year that were mainly attributed to the northwestern counterclockwise water circulation of the Arabian Gulf, and wind direction and intensity. The temporal variation of Kuwait SST was greatly influenced by the seasonal variation of solar intensity and air temperatures. Kuwait SDD was measured through two steps: first, computing the diffuse light attenuation coefficient at 490 nm, $K_d(490)$, and 488 nm, $K_d(488)$, derived from SeaWiFS and MODIS, respectively, using a semi-analytical algorithm; second, establishing two SDD models based on the empirical relationship

of K_d(490) and K_d(488) with *in situ* SDD data. K_d(490) and K_d(488) showed a significant relationship with *in situ* SDD data (r^2= 0.67 and r^2= 0.68, respectively). Kuwait SDD images showed distinct spatial and temporal patterns of Kuwait water clarity that were mainly attributed to three factors: the Shatt Al-Arab discharge, water circulation, and coastal currents.

The SeaWiFS and MODIS data compared to *in situ* measurements provided a comprehensive view of the studied seawater characteristics that improved their overall estimation within Kuwait's waters. Also, the near-real-time availability of SeaWiFS and MODIS data and their highly temporal resolution make them a very advantageous tool for studying coastal environments. Thus, I recommend involving this method in monitoring Kuwait coastal environments.

To my dear parents who guided me to the right path in life

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To the three candles in my life,

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Table of Contents

List of Tables

List of Figures

Chapter 1: An Introduction to the Marine Environment of Kuwait

Chapter 2: Mapping Spatial and Temporal Distributions of Kuwait SST Using MODIS Remotely Sensed Data

Chapter 1

An Introduction to the Marine Environment of Kuwait

Introduction

The Kuwait coastal environments in northwestern Arabian (Persian) Gulf are very productive environments that provide the State of Kuwait with food, freshwater (by desalination), and electrical power. Kuwait seawaters are rich in a diversity of fishery species that provides about 40 to 50% of the country's seafood demand (Al-Yamani *et al*., 2004). Kuwait relies on desalination stations and power plants along the coast for its freshwater supply and electrical power. During the last three decades, the Kuwait marine environments were impacted by critical factors (consequences of three major wars, destruction of Iraqi marshes, reduction of the Shatt Al-Arab discharge, and increased anthropogenic activities) that threatened the sustainability of these environments. Given the extreme importance of these productive environments, and all factors threatening their sustainability, a synoptic environmental monitoring program needed to be developed and implemented.

An efficient environmental program should be designed to comprehensively monitor the water characteristics that affect all aspects of the marine environment. Sea surface temperature (SST) and water clarity are important indicators of water quality and, thus highly influence the coastal ecosystem (Chen *et al*., 2007; Gentilhomme and Lizon, 1998). These water characteristics influence the productivity of marine organisms and explain behaviors of many marine organisms. Studying SST and water clarity can greatly helps understanding fundamental biological and ecological factors, such as the spawning time, and prey-predator interactions (Abou-Seedo *et al*., 1990; Dippner, 1997; Van De Meutter *et al*., 2005). SST and water clarity are also very important habitat characteristics in coastal environments (Brager *et al*., 2003; Riegl *et al*., 2006). Thus, understanding the spatial and temporal variability of these two fundamental water characteristics greatly helps illustrating relationships among the biotic and abiotic factors in coastal ecosystems and consequently providing a better understanding to the coastal environment (Chen *et al*., 2007; Sanden and Hakansson, 1996).

Traditional methods of collecting SST and water clarity data are logistically challenging and do not provide a high spatial-temporal synoptic perspective of these water characteristics. In recent years, oceanographers and marine biologists have begun using remotely sensed imagery to study the water quality of ocean and coastal environments (Gower, 2006). Remotely sensed data have added valuable contributions in understanding the aquatic ecosystems: they provide comprehensive perspectives of fundamental aquatic characteristics, such as SST and water clarity. Also, their highly temporal resolution makes them a very advantageous tool for studying coastal environments. Integrating remotely sensed data and *in situ* measurements can greatly facilitated investigating marine environments (e.g., Chen *et al*., 2007; Marcello *et al*., 2004). Thus, methodologies providing an accurate comprehensive perspective of the SST and water clarity of Kuwait marine environment, such as the integration of ground truth and remotely sensed data, are greatly needed (Al-Yamani *et al*., 2004; Nezlin *et al*., 2007).

Challenges Facing Kuwait's Coastal Environments

The Kuwait coastal environments are very productive environments that provide the State of Kuwait with food, freshwater (by desalination), and electrical power. During the last three decades, these environments have been impacted by critical factors threatening the sustainability of these environments. Among these critical factors, consequences of three major wars, destruction of Iraqi marshes, reduction of the Shatt Al-Arab discharge, and increased anthropogenic activities were the most critical challenges facing Kuwait's coastal environments.

The Gulf War II (the most environmentally devastating war) in 1991 altered the chemical and physical characteristics of Kuwait's marine ecosystems. During that war, the Iraqi army pumped about eight million barrels of Kuwait oil into the Arabian Gulf and set all the oil wells on fire, which caused an environmental disaster not only in Kuwait, but also throughout the region (e.g., Al-Ghadban and El-Sammak, 2005; El-Baz and Al-Sarawi, 2000). The large quantity of oil pumped into the Gulf was a major threat to the desalination stations along the Arabian Gulf: two million barrels of oil were recovered at two locations about 400 km away from Kuwait City near Jubail and Duhran in Saudi Arabia (El-Baz and Al-Sarawi, 2000). Environmental consequences of these oil spills were left throughout the region for many years (Heil *et al*., 2001; Hussain and Gondal, 2007; Mostafawi, 2001).

The marine environment of Kuwait also encountered critical environmental changes when the Iraqi government started draining the Mesopotamian marshlands (locally named Al-Ahwar) in the early1990s through an artificial canal called the

Third River that diverts Euphrates waters before reaching the marshes through another artificial canal called Shatt Al-Basra to the Khor Al-Zubair (Figure 2) (Al-Hilli *et al*., 2009; Al-Yamani *et al*., 2004). The marshlands had covered an area of over 15,000 km^2. Most of these marshlands extend into southern Iraq at the confluence of the Euphrates and Tigris Rivers (Al-Hilli *et al*., 2009). Prior to their destruction, these marshlands served as critical habit for many plants, wildlife, and the domesticated animals of about 400,000 Ma'dans (Marsh Arabs) whose ancestors are believed to date back 5,000 years to the Sumerian civilization that developed the first alphabet and gave rise to the Babylonians (Ali, 2003). In 1995, satellite images showed that 90% of the Mesopotamian marshlands were dried (Al-Hilli *et al*., 2009).

These marshlands are considered among the most important marshlands in the world. They served as natural sediment and chemical pollutant filters to the effluents of the Euphrates River, but after their destruction, sediments, chemicals and wastewater flowed unimpeded from the Euphrates River through the drainage canals into the Khor Al-Zubair that empties into the Arabian Gulf near the Khor Al-Subbiya (Al-Ghadban and El-Sammak, 2005; Al-Yamani *et al*., 2004). The sea currents move these waters through the Khor Al-Subbiya into Kuwait Bay where over the past two decades they have had multiple impacts on aquatic plants and animals, especially in the northern marine environments of Kuwait (Beg and Al-Ghadban, 2003).

Moreover, the reduction of Shatt Al-Arab discharge due to upstream massive dam constructions has threatened the environmental balance of Kuwait marine ecosystems. The Shatt Al-Arab discharge, the main freshwater input in the north

Arabian Gulf, used to play a valuable role in decreasing the salinity and supporting Kuwait seawaters with nutrients that made these environments optimum habitats for many marine organisms (Al-Yamani, 2008; Al-Yamani *et al*., 2004). The Shatt Al-Arab is formed by three rivers: the Euphrates, Tigris, and Karun (Figure 3). These rivers during the past few decades have experienced increasing dam constructions that has reduced and changed the quality of the freshwater flow through these rivers (Al-Hilli *et al*., 2009; Ertunc and Cetin, 2007; Foltz, 2002; Kangi and Heidari, 2008; Kibaroğlu, 2007; Kucukmehmetoglu, 2009; Lapshin, 2000).

The extensive regulation of the Euphrates, Tigris, and Karun Rivers is also expected to change the temporal variation of the Shatt Al-Arab discharge. Pre-1980 studies revealed that the Shatt Al-Arab inflow increased during December through June, with maximum discharge in May, because of heavy rainfall in the winter and melting of snow in Turkey, Syria, Iraq, and Iran in the spring (Al-Yamani *et al.*, 2004). Today, the spring flood is almost completely stored in reservoirs in the upstream countries where it used for drinking and irrigation during the dry months; while in winter, the river flow is released to generate hydro-electrical power (Kangi and Heidari, 2008; Lapshin, 2000; Rahi and Halihan, 2009) that causes the Euphrates to reach its maximum discharge in the winter rather than in the spring (Lapshin, 2000).

These new regulatory procedures are expected to increase the Shatt Al-Arab discharge in the winter months; and consequently, to cause the Kuwait seawater characteristics, such as salinity and nutrient concentrations, to fluctuate. The expected variation of the Shatt Al-Arab discharge agrees with the recent maximum salinity of northern Kuwait seawaters that occurs during February as reported by Al-Yamani *et al*. (2004) and Al-Yamani and Khvorov (2007) (Figure 4).

The marine environments of Kuwait are also experiencing extensive disturbance due to development accompanied by increasing commercial, industrial, and recreational activities that are associated with human population growth. These activities place increased environmental stress on the marine ecosystem through the release of more sewage and increase in water temperatures that are elevated by nearby power plants (Bu-Olayan *et al*., 2001). The growing pressure on the coastal environment is suspected to be associated with documented massive fish die-offs that occurred in October, 1999 and September, 2001(Heil *et al*., 2001; Qasem, 2003; Rao *et al*., 2003). Heil *et al.* (2001) stated that the cause of the first fish die-off is unknown and might be related to one or a combination of factors, including the water currents that enhance transportation of pollutants from Iranian waters into Kuwait waters, increased organic nutrients, residual oil pollutants, undocumented pollutants discharged from the Khor Al-Zubair area, and increased urban waste including sewage and industrial waste.

Previous Studies

SST and Water Clarity

Coastal environments are very productive aquatic ecosystems enriched with the most economically significant fish diversity in the world (Kishino *et al*., 2005). The productivity of these environments also attracts greater anthropogenic activities:

as a consequence, the majority of the world population is concentrated within only 60 km from coasts (Miller *et al*., 2005). The growing value of coastal environments due to global population growth also attracts the interest of marine scientists who have a growing concern about changing physical and chemical attributes of these systems. These scientists often rely on measurements of SST and water clarity that influence the productivity and dynamics of these ecosystems.

SST as an important characteristic of coastal habitats can explain many coastal organism behaviors (Brill *et al*., 2002). Brager *et al*. (2003), for instance, found that coastal dolphin movements were influenced by SST and water clarity. Dippner (1997) indicated that rapid decrease in SST delays fish spawning time for two weeks in the North Sea. Studying SST is also a key factor of understanding global and regional climatic patterns (e.g., Nguyen *et al*., 2007; Thomas *et al*., 2000; Yeh and Kirtman, 2004).

Riegl *et al*. (2006) stated that SST is a fundamental indicator of understanding coastal coral reefs near the Dubai coast. Yimin *et al*. (1999) studied the optimum shrimp habitat depth, temperature, and salinity in Kuwait coastal environment and concluded that shrimps are restricted to certain range of depth, temperature, and salinity. Nasrallaha *et al*. (2001) were able to develop a statistical model using SST to predict over 70% of winter precipitation in Kuwait.

Water clarity that influences the photic zone- the depth of water where the light is sufficiently available- is controlled by several factors including phytoplankton abundance, suspended sediments, detritus, and dissolved organic matter that impede light penetration by absorption, diffusion, and reflectance (Gower, 2006; Miller *et al*., 2005; Ustin, 2004). In 1866, an Italian scholar named Angelo Secchi created a disk to measure the depth of light penetration in water as a tool of measuring water clarity. Thereafter, this tool became very popular in scientific communities because of its simplicity and low cost. The tool remains one of the fundamental instruments to study the water clarity in spite of emerging new technologies for measuring water clarity (Holmes, 1970; Preisendorfer, 1986).

Preisendorfer (1986) developed an equation to derive Secchi Disk Depth (SDD) using diffuse light attenuation, K_d. Megard and Berman (1989) examined the correlation between marine algae, SDD, and K_d in the southeastern Mediterranean Sea, and concluded that the secchi disk provides accurate measurements of water clarity comparable with measurements derived by K_d. Sanden and Hakansson (1996) found a clear inverse relationship between chlorophyll concentrations, an indicator of phytoplankton biomass, and SDD over long term study period in the Baltic Sea.

Factors influencing water clarity of the Arabian Gulf have been addressed in many studies. Sohrabpour *et al*. (2004) studied sediment samples near Bushier Nuclear Power Plant to provide an important report about the environmental situation of the area before the establishment of the nuclear power plant. Al-Ghadban and El-Sammak (2005) examined the spatial distribution of suspended sediments in Kuwait Bay at 12 sites in 1989 and 1992 and observed that suspended sediment concentrations in Kuwait Bay dramatically increased after the Gulf War II. Beg and Al-Ghadban (2003) observed the Kuwait coastal environmental response to the drainage of Iraqi marshes by examining the quality of sediments at 20 sites in the northern part of Kuwait seawaters and found that their samples were characterized by toxicity.

Several studies in the Arabian Gulf focused on water clarity and its role in the marine environment. Shriadah and Al-Ghais (1999) studied water clarity and other seawater characteristics of the United Arab Emirates. Abou-Seedo *et al*. (1990) found that fish abundance and distribution at two study sites in Kuwait Bay were highly related to the water clarity variation.

Marine Studies Using Remotely Sensed Data

The collection of *in situ* data from the marine environment can present many logistical challenges. Many of the earlier cited studies were handicapped by the inability to capture field data in a timely, spatially dense, and geographically referenced format. In recent years, oceanographers and marine biologists have begun using remotely sensed imagery to study the water quality of ocean and coastal environments (Gower, 2006). Remotely sensed data have added valuable contributions in understanding the aquatic ecosystems: they provide comprehensive perspectives of fundamental aquatic characteristics, such as SST and water clarity. Remotely sensed methodologies used to detect these components were developed based on physical, statistical, and environmental factors.

SST, more specifically the skin temperature of the seawater, can be remotely detected by thermal infrared (IR) sensors through two spectral regions: long-wave IR (LWIR 10.0 – 12.2 µm), and short-wave IR (SWIR 3.7 – 4.2 µm) (Miller *et al*., 2005). SST can accurately be estimated by comparing satellite data either with *in situ* data measured by thermometers, or with data derived from radiometers that detect the radiometric skin temperature of the seawater. Current SST algorithms applied to Advanced Very High Resolution Radiometer (AVHRR) and Moderate Resolution Imaging Spectroradiometer (MODIS) (Aqua and Terra) can estimate SST with accuracy of about 0.6^{o}C (Marcello *et al*., 2004). Minnett *et al*. (2004) state that the accuracy of day SST and night SST (SST4) algorithms (less than 0.6^{o}C) derived from MODIS (Aqua and Terra) is acceptable for many marine applications.

Satellite SST data have facilitated comprehensive marine and climatologic studies. Brill *et al*. (2002) studied the vertical and horizontal movements of juvenile tuna near the North Carolina coast based on SST derived from AVHRR and other environmental conditions and were able to specify the SST range that restricts the juvenile tuna movements within a satisfactory accuracy. Pearce *et al*. (2006) used SST derived from AVHRR to analyze the correlation between atmospheric temperatures and SSTs near Rottenest Island, Australia over seven years. Barre *et al*. (2006) found that ocean currents of the southwestern Atlantic, near Brazil, were detectable using MODIS SST and chlorophyll images.

Water clarity can be remotely estimated using the light diffuse attenuation coefficient, $K_d(\lambda)$, at ~ 490 nm that is derived using three methods. The first method derives $K_d(\lambda)$ empirically based on the relationship between $K_d(490)$ and a blue-green band ratio. The second method calculates chlorophyll concentration based on an empirical blue-green band ratio algorithm and use the calculated value as input in another empirical algorithm to derive $K_d(\lambda)$ (Lee *et al*., 2005a). The third method is a semi-analytical approach that calculates the backscattering and absorption coefficients from the remote-sensing reflectance and inserts them in a semi-analytical algorithm to derive $K_d(\lambda)$ (Lee *et al*., 2005a; Lee *et al*., 2005b). The first method is used to calculate the operational (default) ocean product of $K_d(\lambda)$ in Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and MODIS.

Dareckia and Stramski (2004) found that $K_d(\lambda)$ derived from the SeaWiFS and MODIS operational algorithm showed acceptable accuracy in the Baltic Sea. Chen *et al.* (2007) stated that the semi-analytical algorithm is more accurate than the empirical method in detecting water clarity in Case 2 environments, such as Tama Bay where the optical appearance of waters is associated with components such as detritus and colored dissolved organic matter (CDOM) rather than associating with only phytoplankton as in open oceans, Case 1 waters (Miller *et al*., 2005). Pierson *et al*. (2008) modeled photosynthetically available radiation, K_d (PAR), in the Baltic Sea using $K_d(490)$ derived from SeaWiFS.

Marine studies relying on remotely sensed data in the Arabian Gulf, especially in Kuwait waters, are not common although the interest in using remotely sensed data in this region has increased in recent years. Al-Ghadban (2004) used Landsat and SPOT remotely sensed data to assess suspended sediment distributions in 1989 and 1993 using 13 sites in Kuwait Bay. He stated that the study can be considered as an example of using remote sensing in coastal studies in the northern part of the Arabian Gulf. Nezlin *et al*. (2007) studied chlorophyll concentrations, K_d (PAR), and SST of the Arabian Gulf region at global resolution (9 and 4.5 km) using SeaWiFS, AVHRR, and MODIS from September 1997 to May 2006. They stated that future marine studies in the Arabian Gulf using remotely sensed data need to be validated using ground truth data. Al-Yamani *et al*. (2004) also believed that there is a need to establish relationships between *in situ* measurements and remotely sensed data so that a better understanding of this particular region of the Arabian Gulf can be achieved.

Overall Project Goal

Previous oceanographic studies in the northwestern Arabian Gulf have been limited by the lack of establishing multitemporal analysis and using remote sensing technologies, especially the integration of *in situ* measurements with remotely sensed data (Al-Yamani *et al*., 2004; Nezlin *et al*., 2007). As a consequence, the spatial-temporal variability of important seawater characteristics, such as SST and water clarity, in this region remains unknown, or at least, their estimation remains scientifically insufficient. To my knowledge, empirical remotely sensed models measuring water clarity and SST within the northwestern Arabian Gulf waters have not been established. Based on limitations in estimating SST and water clarity described above, the goals of this study are to: 1) develop empirical models for measuring SST and water clarity of Kuwait seawaters; 2) map the spatial and temporal distributions of these water characteristics; and 3) assess the interrelationships between these two water characteristics, by addressing the following questions:

1. What is the relationship between remotely sensed spectral measurements and *in situ* measurements of SST and water clarity in the Kuwait ocean coastal region?
2. Does this relationship vary spatially and/or temporally?

If a relationship between remotely sensed spectral measurements and *in situ* SST and water clarity can be established, the following questions will also be addressed:

3. What factors influence SST and water clarity model accuracy?
4. How does the accuracy of these modeled seawater characteristics vary spatially and/or temporally?
5. What are the spatial and temporal distributions of these Kuwait seawater characteristics?
6. What are the interrelationships between SST and water clarity of Kuwait seawaters?

Dissertation Chapter Summaries

Chapter 1: An Introduction to the Marine Environment of Kuwait

This chapter explains the significance of Kuwait marine environments and the challenges threatening these environments. The chapter also presents previous findings including the advantages of remotely sensed studies, a fundamental background of Kuwait marine environments, the roles of surrounding ecosystems on these environments, and the project goals.

Chapter 2: Mapping Spatial and Temporal Distributions of Kuwait SST Using MODIS Remotely Sensed Data

This chapter presents an evaluation of using *in situ* and MODIS SST data in mapping Kuwait SST. MODIS SST images were matched with *in situ* measurements using linear regression to model Kuwait SST. The Kuwait SST model was tested for statistical robustness using dummy variable analysis and 3-fold cross validation. The Kuwait SST model was then used to map the spatial and temporal distributions of Kuwait SST.

Chapter 3: Modeling Kuwait Seawater Clarity: A Spatial-Temporal Study Using Remote Sensing and GIS

This chapter evaluates the use of *in situ* and remotely sensed data in modeling Kuwait seawater clarity. K_d(488) and K_d(490) semi-analytical algorithms derived from SeaWiFS and MODIS, respectively, were matched with *in situ* measurements using power regression to model SDD within Kuwait waters. The two models derived from SeaWiFS and MODIS were tested for statistical robustness using dummy variable analysis and leave-one-out cross validation. The models were then used to map the spatial and temporal variations of Kuwait seawater clarity. Finally, the interrelationship among water clarity, SST, and chlorophyll concentrations was studied.

Chapter 4: Project Conclusions

This chapter presents overall project conclusions.

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Table 1. Wind directions and their percentage of occurrence in Kuwait during the period of 1962-1986. Each season includes the following months: winter (December, January, and February), spring (March, April, and May), summer (June, July, and August), and fall (September, October, and November) (Al-Yamani *et al*, 2004).

Season	NW	NE	SE	SW	Calm	Variable
Winter	42	10	21	9	16	2
Spring	31	17	27	13	10	2
Summer	63	8	9	10	8	2
Fall	38	14	18	12	15	3

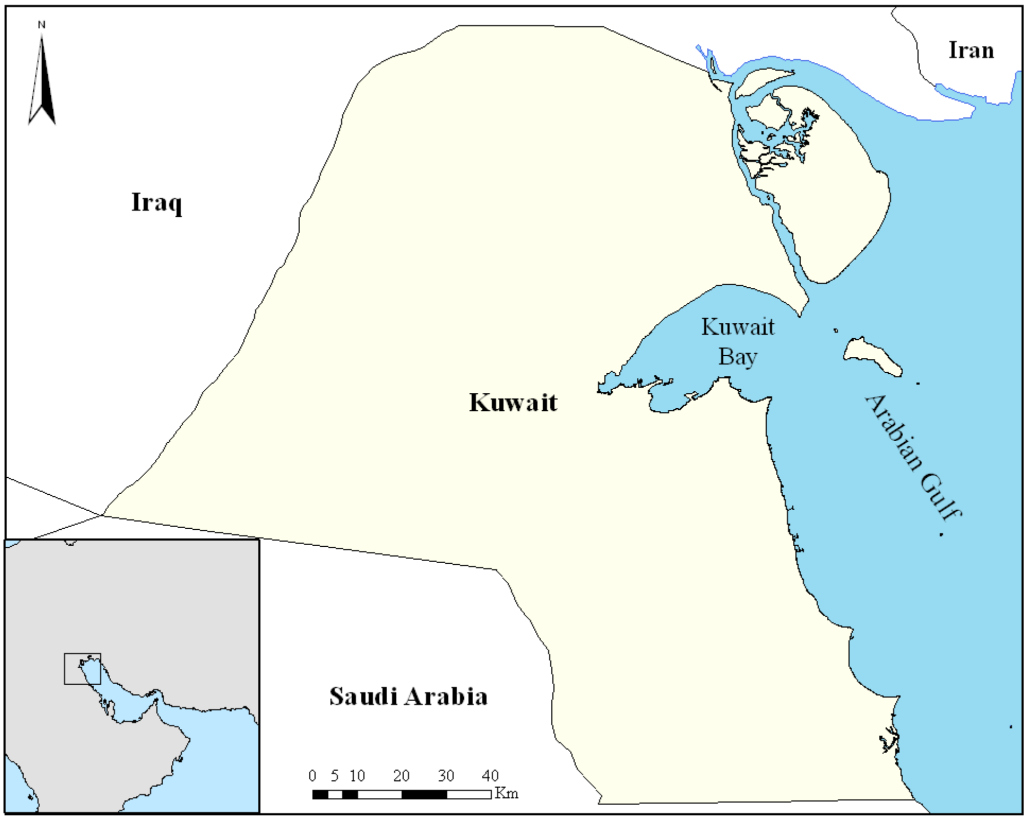

Figure 1. The geographical location of the State of Kuwait and the surrounding countries.

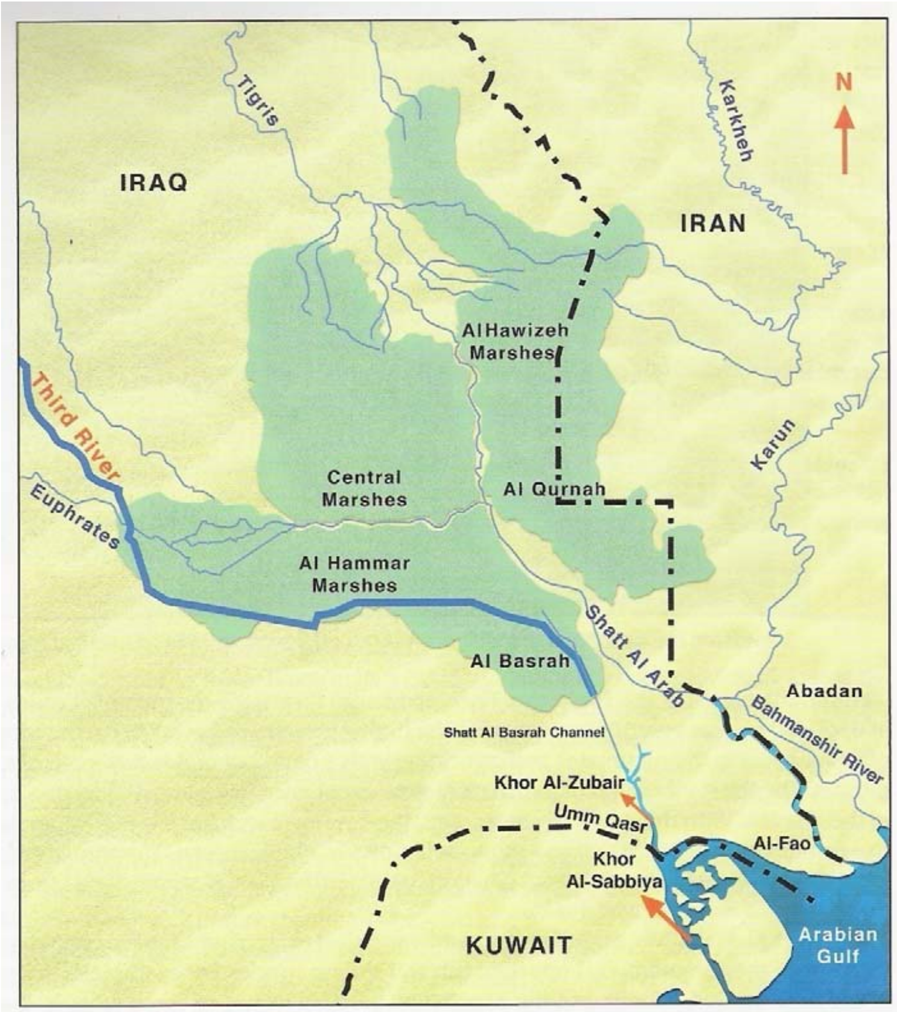

Figure 2. Areas of northern Kuwait and southern Iraq. The area in light green represents the geographic distribution of the Mesopotamian marshlands. Third River diverts Euphrates waters before reaching the marshes through Shatt Al Basra to Khor Al Zubair (Al-Yamani *et al*., 2004).

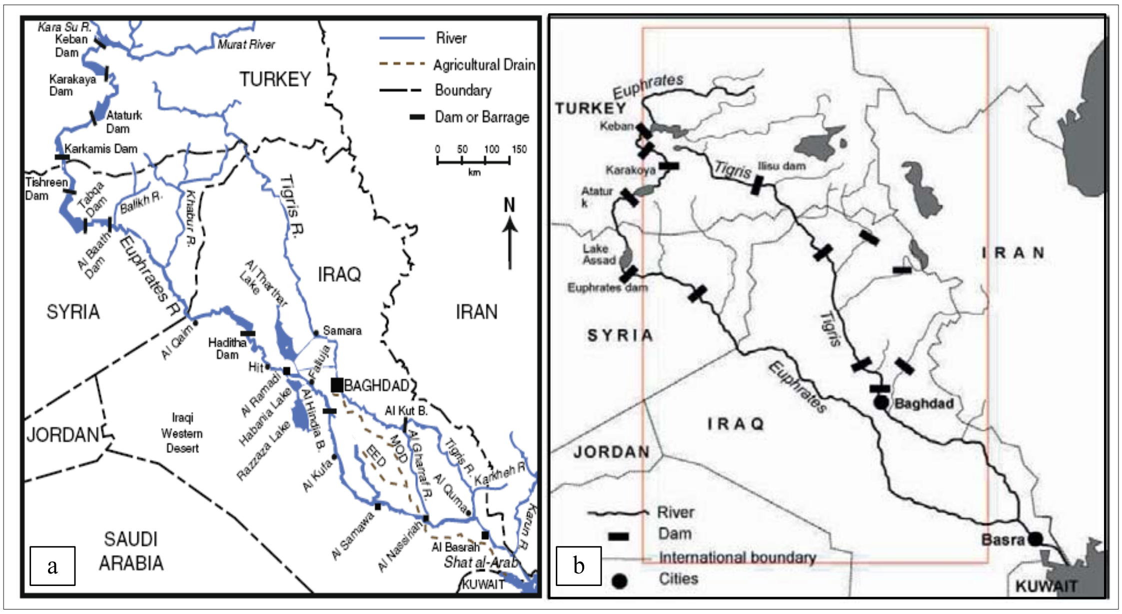

Figure 3 a and b. show complementary information of dams' locations in the Euphrates and Tigris Rivers presented in Rahi and Halihan (2009) and Aydin and Ereker (2009), respectively.

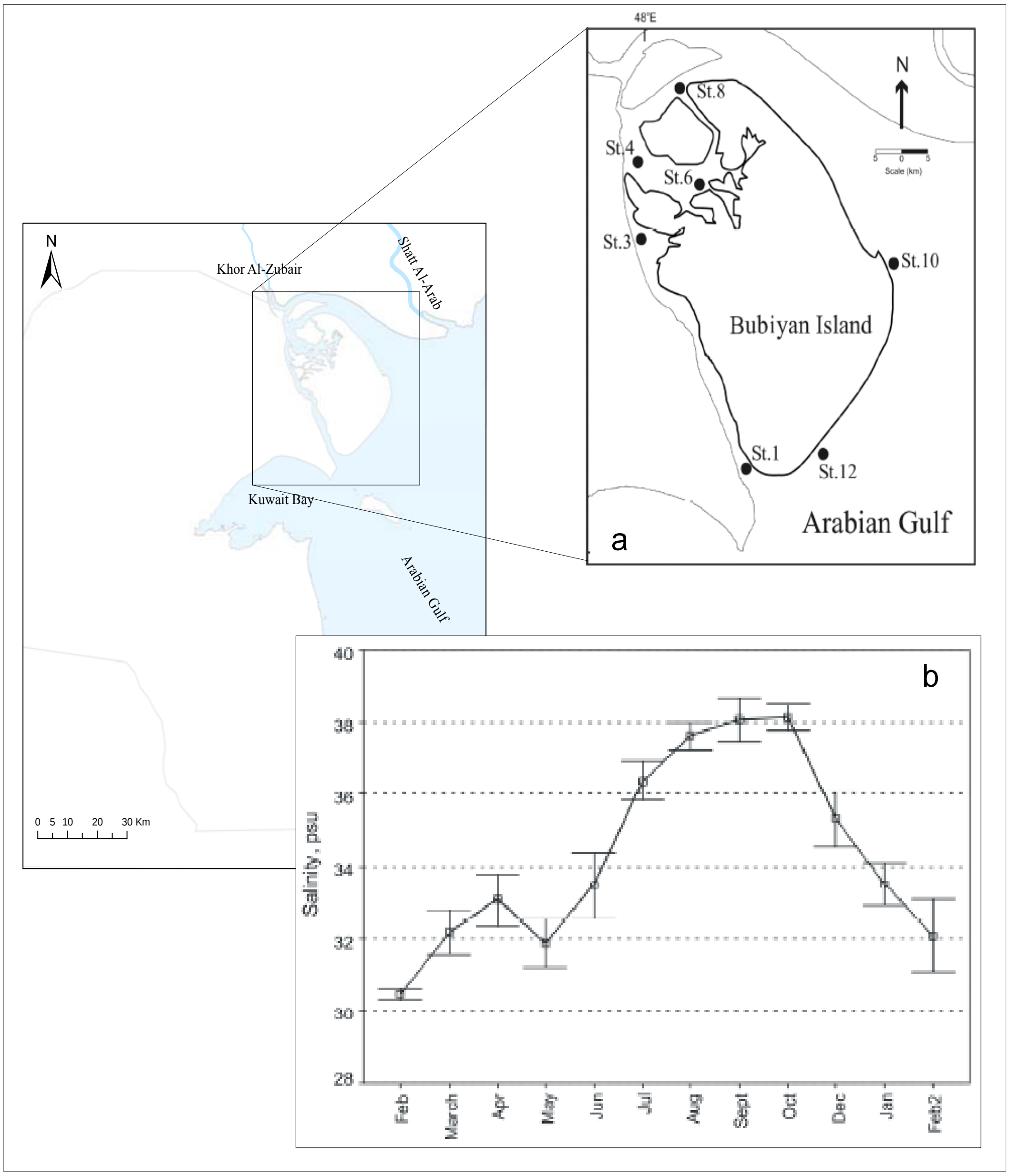

Figure 4. a) Al-Yamani and Khvorov (2007) study sites in north Kuwait seawaters near the Khor Al-Zubair and Shatt Al-Arab. b) Average salinity of the study sites from February, 2004 to February, 2005. Al-Yamani *et al*. (2004) also reported that the minimum salinity of north Kuwait seawaters during the period of 1996-1997 was in February 1997. The second decline of the salinity in May might be attributed to the remaining spring flood reaching the north Arabian Gulf through the Shatt Al-Arab River.

Chapter 2

Mapping Spatial and Temporal Distributions of Kuwait SST Using MODIS Remotely Sensed Data

Abstract

Kuwait sea surface temperature (SST) is an important water characteristic that affects the productivity of marine organisms and explains part of their behaviors. The spatial and temporal distributions of this important water characteristic should be well understood to obtain a better knowledge about this productive coastal environment. The aim of this project was therefore to study the spatial and temporal distributions of Kuwait SST using Moderate Resolution Imaging Spectroradiometer (MODIS) images collected from January 2003 to July 2007.

Kuwait SST was modeled based on the linear relationship between level 2 MODIS SST data and *in situ* SST data that I collected from the study area during July 2007 and those collected by the Kuwait Environmental Public Authority (EPA) between January 2003 and June 2007. MODIS SST images showed a significant relationship with *in situ* SST data (r^2= 0.98, n = 118, RMSE = 0.7 °C). Kuwait SST images derived from MODIS data showed that northern Kuwait's waters including Kuwait Bay had lower SSTs compared with southern waters, especially south offshore waters. This spatial arrangement was dominant in the winter, middle and later summer, and fall, whereas in spring, especially in March and April, this spatial arrangement was totally reversed. May and June seemed to be a transition period between the two patterns. The spatial arrangement of Kuwait SST was mainly

attributed to the northwestern counterclockwise water circulation of the Arabian Gulf, and wind direction and intensity. Kuwait SST exhibited the highest spatial variability in November and December, while the lowest spatial variability of SST was observed in February and March. The temporal variation of Kuwait SST was greatly influenced by the seasonal variation of solar intensity and air temperatures. Kuwait SST increased from January to August, and then decreased to December. The MODIS data comparing to *in situ* measurements provided a comprehensive view of Kuwait SST that improved the estimation of overall SST mean within Kuwait waters and provide better understanding of the water circulation on this important water characteristic. Thus, I recommend involving this method in monitoring Kuwait coastal environments.

Introduction

The Kuwait coastal environments in northwestern Arabian (Persian) Gulf are very productive environments that provide the State of Kuwait with food, freshwater (by desalination), and electrical power. Kuwait seawaters are rich in a diversity of fishery species that provides about 40 to 50% of the country's seafood demand (Al-Yamani *et al*., 2004). Kuwait relies on desalination stations and power plants along the coast for its freshwater supply and electrical power. During the last three decades, the Kuwait marine environments were impacted by critical factors (consequences of three major wars, destruction of Iraqi marshes, reduction of the Shatt Al-Arab discharge, and increased anthropogenic activities) that threatened the sustainability of these environments. Given the extreme importance of these productive environments, and all factors threatening their sustainability, a synoptic environmental monitoring program needed to be developed and implemented.

An efficient environmental program should be designed to comprehensively monitor the water characteristics that affect all aspects of the marine environment. One of the most basic and yet important coastal water characteristic is sea surface temperature (SST) that affects the productivity of marine organisms and explains their behaviors (e.g., Dippner, 1997; Lalli and Parsons, 1997; Mccafferty *et al*., 1999; Santos *et al*., 2006). Traditional methods of collecting SST data within Kuwait waters are logistically challenging and do not provide a high spatial-temporal synoptic perspective of SST. Thus, methodologies providing an accurate comprehensive perspective of the Kuwait SST, such as the integration of ground truth and remotely sensed data, are greatly needed (Al-Yamani *et al*., 2004; Nezlin *et al*., 2007).

SST as an important characteristic of coastal habitats can explain many coastal organism behaviors (Brill *et al*., 2002). Brager *et al*. (2003), for instance, found that coastal dolphin movements were influenced by water clarity and SST. Dippner (1997) indicated that rapid decrease in SST delays fish spawning time for two weeks in the North Sea. Studying SST is also a key factor in understanding global and regional climatic patterns (e.g., Nguyen *et al*., 2007; Thomas *et al*., 2000; Yeh and Kirtman, 2004).

Riegl *et al*. (2006) stated that SST is a fundamental indicator of understanding coastal coral reefs near the Dubai coast. Yimin *et al*. (1999) studied the optimum shrimp habitat depth, temperature, and salinity in Kuwait coastal environment and concluded that shrimps are restricted to certain range of depth, temperature, and salinity. Nasrallaha *et al*. (2001) were able to developed statistical model using SST to predict over 70% of winter precipitation in Kuwait.

The collection of *in situ* data from the marine environment can present many logistical challenges: marine studies relying merely on *in situ* measurements are handicapped by the inability to capture field data in a timely, spatially dense, and geographically referenced format. In recent years, oceanographers and marine biologists have begun using remotely sensed imagery to study the water quality of ocean and coastal environments (Gower, 2006). Remotely sensed data have added valuable contributions in understanding aquatic ecosystems. They provide comprehensive perspectives of fundamental aquatic characteristics, such as SST. Remotely sensed methodologies used to detect these components were developed based on physical, statistical, and environmental factors.

SST, more specifically the skin temperature of the seawater (a few micrometers) (Chan and Gao, 2005), can be remotely detected by thermal infrared (IR) sensors through two spectral regions: long-wave IR (LWIR 10.0 – 12.2 μm), and short-ware IR (SWIR 3.7 – 4.2 μm) (Miller *et al*., 2005). SST can accurately be estimated by comparing satellite data either with *in situ* data measured by thermometers, or with data derived from radiometers that detect the radiometric skin temperature of the seawater (e.g., Haines *et al*., 2007; Minnett *et al*., 2004; Minnett *et al*., 2002). Marcello *et al*. (2004), however, suggested that *in situ* SST should be used in validating remotely derived SST only when the wind speed exceeds 6 m^{-s} to minimize the skin temperature effect- the difference between the skin surface temperature detected by the infrared remotely sensed data and the top sea surface layer (1 to 0.5 m) detected by the thermometer. Skin temperature effect can produce some degree of error under some conditions, such as seawater thermal stratification (Donlon *et al*., 2002).

Current SST algorithms applied to Advanced Very High Resolution Radiometer (AVHRR) and Moderate Resolution Imaging Spectroradiometer (MODIS) (Aqua and Terra) can estimate SST with an accuracy of about 0.6^{o}C (Marcello *et al*., 2004). Minnett *et al*. (2004) state that the accuracy of day SST and night SST (SST4) algorithms (less than 0.6^{o}C) derived from MODIS (Aqua and Terra) is acceptable for many marine applications.

Satellite SST data have facilitated comprehensive marine and climatologic studies. Brill *et al*. (2002) studied the vertical and horizontal movements of juvenile tuna near the North Carolina coast based on SST derived from AVHRR and other environmental conditions and were able to specify the SST range that restricts the juvenile tuna movements within a satisfactory accuracy. Pearce *et al*. (2006) used SST derived from AVHRR to analyze the correlation between atmospheric temperatures and SSTs near Rottenest Island, Australia over seven years. Barre *et al*. (2006) found that ocean currents of the southwestern Atlantic, near Brazil, were detectable using MODIS SST and chlorophyll images. Martinez-Diaz-De-Leon *et al*. (1999) found that remotely sensed SST was an efficient tool in studying water circulation in the Gulf of Tehuantepec, Mexico.

Marine studies relying on remotely sensed data in the Arabian Gulf, especially in Kuwait waters, are not common although the interest in using remotely sensed data in this region has increased in recent years. Al-Ghadban (2004) used Landsat and SPOT remotely sensed data to assess suspended sediment distributions in 1989 and 1993 using 13 sites in Kuwait Bay. He stated that the study can be considered as an example of using remote sensing in coastal studies in the northern part of the Arabian Gulf. Nezlin *et al*. (2007) studied chlorophyll concentrations, K_d (PAR), and SST of the Arabian Gulf region at global resolution (9.0 and 4.5 km) using Sea-viewing Wide Field-of-view Sensor (SeaWiFS), AVHRR, and MODIS from September 1997 to May 2006. They stated that future marine studies in the Arabian Gulf using remotely sensed data need to be validated using ground truth data. Al-Yamani *et al*. (2004) also believed that there is a need to establish relationships between *in situ* measurements and remotely sensed data so that a better understanding of this particular region of the Arabian Gulf can be achieved.

Study Goal

Previous oceanographic studies in the northwestern Arabian Gulf have been limited by the lack of multitemporal analysis and use of remote sensing technologies, especially the integration of *in situ* measurements with remotely sensed data (Al-Yamani *et al*., 2004; Nezlin *et al*., 2007). As a consequence, the spatial-temporal variability of important seawater characteristics, such as SST, in this region remains unknown: or at least, their estimation remains scientifically insufficient. To my knowledge, empirical remotely sensed models measuring SST within the northwestern Arabian Gulf waters have not been established. The goals of this study were to: 1) develop an empirical model for measuring Kuwait SST using the SST ocean product of MODIS (Feldman and McClain, 2008); 2) map the spatial and temporal distributions of Kuwait SST for the period of January 2003 to July 2007.

Study Area

The study area located in the northwestern part of the Arabian Gulf in Kuwait seawaters lies within the geographic coordinates of 28^{o} 32' to 29^{o} 50' N and from 47^{o} 34' to 48^{o} 40' E (Figure 1). This area was selected because of availability of seawater quality data that have been collected on a relatively consistent basis for 20 years, and because of my familiarity with the geography of the region. The coastline of Kuwait is about 350 km long including Kuwait Bay that is the most vital area in the country where the urban, commercial and industrial sectors are concentrated (Al-Bakri and Kittaneh, 1998).

The Kuwait seawater depth is shallow (mostly < 30 m) and increases from north to south (Al-Yamani *et al*., 2004). The average water depth in Kuwait Bay is about 5 m with maximum depth of about 30 m near Ras Al-Ard (Figure 2) (Al-Ghadban and El-Sammak, 2005). Kuwait waters are well mixed across the year because of the water shallowness (Al-Yamani *et al*, 2004): thus, thermal stratification does not exist in most of Kuwait waters, except those waters deeper than 30 m (Rao *et al*., 2003) that exhibit thermal stratification during the spring and summer (Al-Yamani *et al*., 2004).

Kuwait seawater including Kuwait Bay is influenced by the wind-dominant counterclockwise circulation in the northwestern Gulf: some different local circulations are also present. Kuwait seawaters have a weak current that ranges from 120 cm s^{-1} in the Khor Al-Subbiya and 40 cm s^{-1} in Kuwait Bay (Al-Yamani *et al*., 2004). The currents in the Bay are classified into two zones, eastern and western. The eastern zone has a relatively higher current velocity and is affected by water inflow from the Shatt Al-Arab River that is characterized by lower salinity and temperature, whereas the western zone has less current velocity and is characterized by increased temperature, salinity, and suspended sediments (Appendix, Figure A) (Al-Ghadban and El-Sammak, 2005).

Climatic conditions are an important influence on the marine environments of Kuwait. Wind speed and direction affect the currents and circulations of Kuwait seawaters (Reynolds, 2002). The northwestern wind is the dominant wind in the northwestern Arabian Gulf that increases in the summer months and decreases in the spring months. The southeastern wind is the second dominant wind in the region that usually occurs in the spring with minimum occurrence in the summer (Al-Yamani *et al*., 2004). Dust storms are an important source of sediments and nutrients that sometimes change the Kuwait seawaters' properties (Rao and Al-Yamani, 1999).

Methodology

In Situ Measurements

The Environmental Public Authority (EPA) of Kuwait has been collecting seawater samples at 13 locations in the waters of Kuwait since 1985. The selection of the geographic locations of the 13 sample sites was determined by the EPA based on their concerns about water conditions near the nation's electrical power and desalination plants and other vital sites. One EPA measurement of particular interest to this study is SST collected from January 2003 to June 2007 with an accuracy of measurement around 0.05 ^{o}C (EPA, 2007). This time period was selected to match satellite data availability.

The 13 EPA stations were divided into three groups. The water quality data of the first group, including stations labeled Z01, Z02, Z03, Z04 and Z05, were collected on the first ten days every month; the data of the second group, including stations Z0, Z06, Z07, Z08 and Z09, were collected on the second ten days of every month; and data collection for sites Z10, Z11 and Z12 was during the last ten days of every month (Figure 1). This schedule was modified from time to time to adjust for inclement weather. The *in situ* data collection and laboratory analysis were performed according to the guidelines published in the Manual of Oceanographic Observations and Pollutant Analyses Methods, ROPME 1999 (MOOPAM).

In addition to the EPA measurements, I used SST data that I collected from the Kuwait waters in July 25, 2007 at eight offshore sites using a HANNA (HI 93510) digital thermometer that has an accuracy of ± 0.4 ^{o}C (Figure 1). The selected date was based on the weather and sea conditions most suitable for safe navigation and taking measurements in these months.

Remotely Sensed Data

MODIS (Aqua) images were used to model the spatial and temporal distribution of Kuwait SST. MODIS level 2 SST ocean products (1 km) collected from January 2003 to July 2007 were downloaded from the Ocean Color Web Database (Feldman and McClain, 2008). To ensure image quality, images a large viewing angle and images acquired during dust storms or cloudy days were disregarded following the image quality restrictions used by Marcello *et al*. (2004). Negative atmospheric conditions were assessed using available metrological data from the Kuwait International Airport (Directorate of Civil Aviation, 2007), about 30 km off the study area, and also by visual assessment of the imagery using natural color band combinations.

Satellite-*in situ* matching

A time window of ±1h was used to match SST *in situ* measurements with MODIS SST images following the time window used by Marcello *et al*. (2004). To ensure the adequacy of the selected time window, the relationship between matched data was tested for constancy over the time. Also, the relationship between matched data was compared with the daily average wind speed measured by Directorate of Civil Aviation (2007) to detect whether the differences between SST images and *in situ* SST vary based on wind speed: this comparison was established to detect the skin temperature effect. The images were matched with *in situ* measurements using the mean of 3x3 pixel array to take into account errors in satellite navigation, and errors due to geophysical variability (Bailey and Werdell, 2006). Arrays with standard deviation > 0.75 °C were excluded from the analysis following the standard deviation value used by Reinart and Reinhold (2008). Figure 3 summarizes the satellite- *in situ* matchup processes.

Data Analysis

Comparison between SST images and in situ SST

The relationship between SST images and *in situ* SST was modeled using linear regression analysis. The spatial and seasonal constancies of the SST model were tested using dummy variable analysis (Montgomery and Peck, 2001; Silk, 1976). The dummy variable analysis was performed to statistically detect: 1) whether the relationship of remotely sensed SST and *in situ* SST in Kuwait Bay (shallow waters) differs from that along the south coast (deeper waters); and 2) whether the relationship of remotely sensed SST and *in situ* SST in Kuwait waters differs from season to season. The regression equation using dummy variable to detect the model's spatial constancy is:

$$In\ situ\ \mathrm{SST} = \beta_0 + \beta_1(\mathrm{MODIS\ SST}) + \beta_2 L \qquad \mathrm{Equation.\ 1}$$

where β_0 is the y-intercept, β_1 is the slope, and β_2 is the change in the y-intercept from Kuwait Bay to the south coast. MODIS SST is the remotely sensed SST derived from MODIS, and L is the dummy variable that equals 0 when comparing *in situ* SST to MODIS SST in Kuwait Bay and 1 when comparing *in situ* SST to MODIS SST in south coast. Thus, the previous equation can be divided into two parts based on the dummy variable (L):

$$\textit{In situ}\ \text{SST} = \begin{cases} \beta_0 + \beta_1\ (\text{MODIS SST}) & \text{If } L = 0 \quad \text{Equation. 2a} \\ (\beta_0 + \beta_2) + \beta_1\ (\text{MODIS SST}) & \text{If } L = 1 \quad \text{Equation. 2b} \end{cases}$$

The model's spatial constancy was tested based on β_2 at the 0.05 level of significance using ANOVA.

The regression equation using dummy variable to detect the model's seasonal constancy is:

$$\textit{In situ}\ \text{SST} = \beta_0 + \beta_1(\text{MODIS SST}) + \beta_2 S + \beta_3 F + \beta_4 W \qquad \text{Equation. 3}$$

where β_2, β_3 and β_4 are the change in the y-intercept in the summer, fall, and winter, respectively. *S, F,* and *W* are the dummy variables used to refer for the summer, fall, and winter, respectively: when *in situ* SSTs observed in summer, for instance, S would equal to 1, and the other dummy variables would equal to 0. Thus, the previous equation can be divided into four parts based on the dummy variables (*S*, *F,* and W):

$$\textit{In situ}\ \text{SST} = \begin{cases} \beta_0 + \beta_1\ (\text{MODIS SST}) & \text{In spring} \quad \text{Equation. 4a} \\ (\beta_0 + \beta_2) + \beta_1\ (\text{MODIS SST}) & \text{In summer} \quad \text{Equation. 4b} \\ (\beta_0 + \beta_3) + \beta_1\ (\text{MODIS SST}) & \text{In fall} \quad \text{Equation. 4c} \\ (\beta_0 + \beta_4) + \beta_1\ (\text{MODIS SST}) & \text{In winter} \quad \text{Equation 4. d} \end{cases}$$

The model's seasonal constancy was tested based on β_2, β_3, and β_4 at the 0.05 level of significance using ANOVA.

The accuracy of the Kuwait SST model derived from MODIS SST was tested using mean and median predicted SST-to-*in situ* SST ratio, mean and median absolute percent difference (PD), and root mean square error (RMSE). The mean and median predicted SST-to-*in situ* SST ratio is used to measure the overall model bias, whereas the mean and median PD is used to measure the model uncertainty (Bailey and Werdell, 2006; Chen *et al*., 2007). The PD is calculated as:

$$PD_i = 100 * \frac{|\widehat{SST}_i - SST_i|}{SST_i} \qquad \text{Equation. 5}$$

where $\widehat{SST}$ is the predicted value derived from MODIS SST, and SST is the *in situ* measurement.

The Kuwait SST model was tested in a simulated environment using 3-1 cross validation in which the dataset was divided into three segments: two of them were selected to build the model, and the remaining segment was used to validate the accuracy of the model. This process was repeated 3 times by switching among the three segments (Camstra and Boomsma, 1992; D'alimonte and Zibordi, 2003; Jonathan *et al*., 2000).

Calculating the overall monthly mean of Kuwait SST

SST MODIS images acquired during the study period were selected based on the image quality criteria discussed earlier to calculate Kuwait SST using the Kuwait SST model. The modeled SST images were used to calculate the overall monthly mean of Kuwait SST. The overall monthly mean was computed as (Figure 4):

$$\mu_{Pij} = \frac{\sum_{I=1}^{n} PV_{Pij}}{n} \qquad \text{Equation. 6}$$

where μ_{Pij} is the mean of the pixel at row $_i$ and column $_j$, I is an SST image, n is the number of images, and PV_{Pij} is the value of Pij.

Result

Comparison between SST images and *in situ* SST

A total of 118 *in situ* SST points were matched with MODIS SST images acquired from January 2003 to July 2007 based on the quality criteria described earlier: 34 matched *in situ* points were in Kuwait Bay, 78 matched *in situ* points were in the south coast, and 6 matched *in situ* points were from offshore sites. The station Z02 was excluded from the analysis because of its adjacency to the shore (Figure 1). The matched *in situ* points were distributed over the four seasons as follows: 25 in spring, 38 in summer, 39 in fall, and 16 in winter.

The relationship between *in situ* SST and MODIS SST was significant (*In situ* SST = 1.0194* MODIS SST – 0.731, r^2 = 0.98) (Figure 5). The median bias = 0.05 ^{o}C, meaning that the MODIS SSTs were warmer than *in situ* SSTs. The mean and median predicted SST-to-*in situ* SST ratio and mean and median PD were 1.00, 1.00, 2.19%, and 1.90%, respectively. The regression RMSE was 0.701 ^{o}C, whereas the RMSE derived from the cross validation analysis was 0.713 ^{o}C (Table 1). These values indicated that the Kuwait SST model can accurately detect SST within Kuwait waters.

The Kuwait SST model residuals over the selected time window illustrated typical random distribution (Figure 6) indicating that the selected time for matching *in situ* SST with MODIS SST was reasonable: the residuals were not ascending toward the end of the time window. Also, the Kuwait SST model residuals against the average daily wind speed illustrated reasonable random distribution (Figure7) indicating that the *in situ* data were not matched with the MODIS SST data under the skin temperature effect. The Kuwait SST model exhibited spatial and seasonal constancies. The dummy variable analysis revealed that the relationship between *in situ* SST and MODIS SST in Kuwait Bay and the south coast was not significantly different (P-value =0.844) (Figure 8). Likewise, the relationship between *in situ* SST and MODIS SST across the seasons was not significantly different (P-value of β_2 =0.182, P-value of β_3= 0.220, P-value of β_4= 0.170) (Figure 9).

SST image series analysis

The overall monthly mean of Kuwait SST images illustrated distinct spatial and temporal distributions. Northern Kuwait's waters including Kuwait Bay had lower SSTs compared with southern waters, especially south offshore waters. This spatial arrangement was dominant in the winter, middle and later summer, and fall, whereas in spring, especially in March and April, this spatial arrangement was totally reversed. May and June seemed to be a transition period between the two patterns (Figure 10). Kuwait SST exhibited the highest spatial variability in November (SD = 1.2 ^{o}C) and December (SD = 1.5 ^{o}C), while the lowest spatial variability of SST was observed in February (SD = 0.3 ^{o}C) and March (SD = 0.3 ^{o}C).

The temporal variation of Kuwait SST was greatly influenced by the seasonal variation of solar intensity and air temperatures. Kuwait SST increased from January (15.4 ^{o}C) and February (15.7 ^{o}C) to August (32.4 ^{o}C), and then decreased to December (18.1 ^{o}C). The lowest monthly mean of the Kuwait SST of 13.3 ^{o}C occurred in January 2007, whereas the highest monthly mean of the Kuwait SST of

32.6 ^{o}C occurred August 2003. Figure 11 shows the difference between the overall monthly mean SST and the monthly mean SST during the study period. The annual mean Kuwait SST was 24.4 ^{o}C with an annual range of 17.1 ^{o}C (Table 2). The temporal variation of overall monthly mean air temperature revealed that there was one month of lag between the highest air temperature (observed in July) and the highest SST (observed in August). Kuwait SST became closer to air temperatures in February and October (Figure 12a &b).

In Kuwait Bay, the spatial distribution of SST was generally influenced by the spatial distribution of Kuwait SST. Kuwait Bay SST exhibited the highest spatial variability in November (SD = 0.7 ^{o}C), while the lowest spatial variability of SST was observed in February (SD = 0.4 ^{o}C), which agreed with those observed for the Kuwait waters. Kuwait Bay SST had the same temporal variation with Kuwait SST. Kuwait Bay SST increased from January (14.6 ^{o}C) to August (32.1 ^{o}C), and then decreased to December (16.6 ^{o}C). The annual mean Kuwait Bay SST was 23.9 ^{o}C with an annual range of 17.5 ^{o}C (Table 2). The overall monthly mean SST derived from MODIS images was distinctly higher than SST derived from *in situ* data in January, February, and April, although both datasets had the same temporal variation (Figure 12c).

In the south coast, the spatial distribution of SST was clearly influenced by the overall spatial distribution of Kuwait SST. South coast SST exhibited the highest spatial variability in December (SD = 1.0 ^{o}C), while the lowest spatial variability of SST was observed in March (SD = 0.2 ^{o}C), which agreed with those observed for the

Kuwait waters. The temporal variation of SST in the south coast agreed with the general temporal variation of Kuwait SST. The south coast SST increased from January (15.5 ^{o}C) and February (15.7 ^{o}C) to August (32.5 ^{o}C), and then decreased to December (18.6 ^{o}C). The annual mean south coast SST was 24.6 ^{o}C with an annual range of 17.1 ^{o}C (Table 2). The overall monthly mean SST derived from MODIS images was distinctly higher than SST derived from *in situ* data in November and December, although both datasets had the same temporal variation (Figure 12d).

Discussion

The Kuwait SST model implications

The Kuwait SST model derived from MODIS thermal remotely sensed data was efficient in mapping the Kuwait SST in all seasons. Although matching MODIS SST data with *in situ* SST measured by the thermometer does not provide the ultimate precision for the remotely estimation of SST, which can be achieved when matching MODIS SST with *in situ* seawater surface skin temperature measured by an infrared radiometer, the precision of Kuwait SST model (±0.7 ^{o}C) is satisfactory for many marine applications (Marcello *et al*., 2004). The Kuwait SST model can be used in many marine applications including coastal marine ecology applications, and marine biology applications (e.g., Brill *et al*., 2002; McCafferty *et al*., 1999; Santos *et al*., 2006; Shaffer *et al*., 2005). Also, the Kuwait SST model can be used as a complementary means to study wind driven water circulations of the northwestern part of the Arabian Gulf (e.g., Barre *et al*., 2006; Martinez-Diaz-De-Leon *et al*., 1999).

I recommend using MODIS (Terra and Aqua) data that are freely available for the academic and research communities, in monitoring Kuwait SSTs. The near-real-time availability of MODIS data and their synoptic spatial and temporal coverage make them a very advantageous tool for the coastal monitoring programs. Thus, integrating MODIS remotely sensed data with *in situ* measurements can add a valuable advancement for the current coastal environmental program of Kuwait.

Spatial and Temporal Distribution of Kuwait SST

The general spatial arrangement of Kuwait SST was mainly attributed to the northwestern counterclockwise water circulation of the Arabian Gulf, and wind direction and intensity. The wind-dominant counterclockwise circulation in the northwestern Gulf plays an important role in moving seawaters from the eastern bank of the Arabian Gulf (Iranian side) to the western bank of the Arabian Gulf (Kuwaiti side) (Al-Yamani *et al*., 2004; Heil *et al*., 2001). The counterclockwise water circulation seemed to move different seawater surface layers parallel to the Kuwait shore, which created a distinct spatial arrangement of Kuwait SST that extended from north to south. This spatial arrangement of Kuwait SST was clearly observed in November and December (Figure 10). Furthermore, the wind direction and intensity play a significant role in enhancing, weakening, or inverting the counterclockwise water circulation, which dominates Kuwait's waters (Al-Yamani *et al*., 2004; Reynolds, 2002). The wind influence on the spatial distribution of Kuwait SST was pronounced, especially when the spatial distribution of Kuwait SST was reversed during March and April (Figure 10). The reversal of Kuwait SST spatial arrangement was most likely due to the southeastern wind, which occurs most frequently (percentage occurrence = 27%) in the spring (Al-Yamani *et al*., 2004). That wind might cause the reversal in the water circulation in March and April.

Wind-wave activity and coastal morphology are other important factors explaining the spatial distribution of Kuwait SST. Wind-wave activity creates the longshore coastal currents (Hakanson and Bryhn, 2008; Segar, 1998; Sverdrup *et al*., 2006) that move southward, which agrees with the general water circulation of Kuwait's territorial waters (Al-Yamani *et al*., 2004). As the longshore coastal currents move southward, they move sea surface layers to the south coast: the longshore coastal currents continue moving southward until they are deflected toward offshore waters by the two headlands in the south (Ras Al-Julaiah and Ras Al-Zour) (Figure 10). The longshore coastal current influence on the spatial distribution of SST near these two headlands was pronounced most of the months, especially in May and June. Thus, the wind direction and intensity can affect the spatial and temporal distribution of Kuwait SST as it varies across the year.

The temporal distribution of Kuwait SST was highly associated with seasonal variations of air temperatures with one month of lag in Kuwait SST when comparing the highest SST to the highest air temperature. This association was due to the heat exchange between sea surface layers and the adjacent atmospheric layers whose effect on seawaters increases intensively in shallow waters (Lalli and Parsons, 1997; Segar, 1998; Sverdrup *et al*., 2006) such as Kuwait waters. The variation of SST due to the difference in water depths within Kuwait waters, however, was only clear when comparing SSTs of the intertidal zone to SSTs of the other areas. Perhaps, this was for either one of these two reasons: the changes occurred in Kuwait SST because of water depth variations was so small that they could not be detected by the Kuwait SST model whose accuracy was equal to 0.7 ^{o}C; or, the effect of water depth variation on Kuwait SST was minimized due to the vertical and horizontal mixing of waters and the water circulation system.

Conclusion

The SST MODIS showed a significant relationship with *in situ* SST data (r^2= 0.98, RMSE = 0.7 ^{o}C). The Kuwait SST model derived from SST MODIS data was efficient in mapping the Kuwait SST in all seasons. The Kuwait SST model can be used in many marine applications including coastal marine ecology applications, and marine biology applications. Also, the model can be used as a complementary means to study wind driven water circulations of the northwestern part of the Arabian Gulf.

The overall monthly mean of Kuwait SST images illustrated distinct spatial and temporal distributions. Northern Kuwait's waters, including Kuwait Bay, had lower SSTs comparing with south waters, especially south offshore waters. This spatial arrangement was dominant in the winter, middle and later summer, and fall, whereas in spring, especially in March and April, this spatial arrangement was totally reversed. May and June seemed to be a transition period between the two patterns. Kuwait SST exhibited the highest spatial variability in November and December, while the lowest spatial variability of SST was observed in February and March. The temporal variation of Kuwait SST was greatly influenced by the seasonal variation of solar intensity and air temperatures. Kuwait SST increased from January to August, and then decreased to December.

In Kuwait Bay, the spatial distribution of SST was generally influenced by the spatial distribution of Kuwait SST. Kuwait Bay SST exhibited the highest spatial variability in November, while the lowest spatial variability of SST was observed in February, which agreed with those observed for the Kuwait waters. Kuwait Bay SST had the same temporal variation with Kuwait SST. Also, the spatial distribution of SST in the south coast was clearly influenced by the overall spatial distribution of Kuwait SST. South coast SST exhibited the highest spatial variability in December, while the lowest spatial variability of SST was observed in March, which again agreed with those observed for the Kuwait waters.

The spatial arrangement of Kuwait SST was mainly attributed to the northwestern counterclockwise water circulation of the Arabian Gulf, wind direction and intensity, wind-wave activity and coastal morphology. The temporal variability of these factors played an important role in understanding the spatial arrangement of Kuwait SST. The temporal distribution of Kuwait SST was highly associated with seasonal variations of air temperatures with one month of lag in Kuwait SST when comparing the highest SST to the highest air temperature. This association was due to the heat exchange between sea surface layers and the adjacent atmospheric layers whose effect increases intensively in shallow waters.

The MODIS data compared to *in situ* measurements provided a comprehensive view of the Kuwait SST that improved the estimation of overall SST mean within Kuwait's waters. Also, the near-real-time availability of SeaWiFS and MODIS data and their highly temporal resolution make them a very advantageous tool for studying coastal environments. Thus, I recommend involving this method in monitoring Kuwait coastal environments.

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Table 1. Shows a summary statistics of the Kuwait SST model.

Study Period	1/2003-7/2007
N	118
r^2	0.98
Mean $\widehat{SST}$/ in situ SST*	1
Median $\widehat{SST}$/ in situ SST	1
Mean PD	2.19%
Median PD	1.90%
Regression RMSE	0.701 ^oC
Cross Validation RMSE	0.713 ^oC

* $\widehat{SST}$ is predicted SDD derived from the SST models.

Table 2. Overall monthly mean SST of Kuwait Bay, South Coast, and Kuwait waters.

	Overall monthly mean SST ^oC		
Months	Kuwait Bay	South Coast	Kuwait waters
January	14.6	15.5	15.4
February	15.5	15.7	15.7
March	18.5	18.3	18.3
April	23.1	22.2	22.4
May	26.9	27.0	27.0
June	28.6	29.4	29.2
July	30.4	31.4	31.2
August	32.1	32.5	32.4
September	29.8	31.2	30.8
October	28.4	29.1	28.9
November	22.1	23.8	23.4
December	16.6	18.6	18.1
Annual Mean	23.9	24.6	24.4
Annual Range	17.5	17.1	17.1

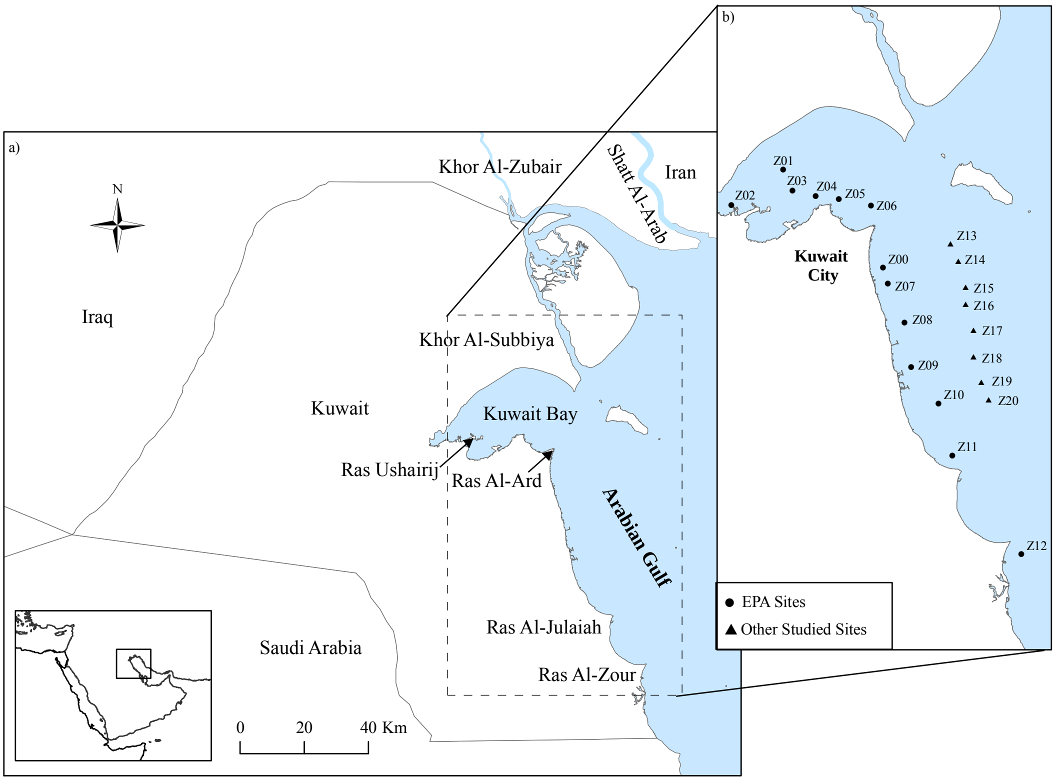

Figure 1. a) Illustrates the study area and major headlands in the south Kuwait Bay and south coast. Note that the Shatt Al-Arab River and Khor Al-Zubair empty in the north of Kuwait's territorial waters. b) Illustrates the study sites from where the *in situ* measurements were collected: study sites with a circle symbol are the EPA sites; and study sites with triangle symbol illustrates the locations of my fieldwork during the summer of 2007. Note that the station Z02 was excluded from the analysis because of its adjacency to the shore.

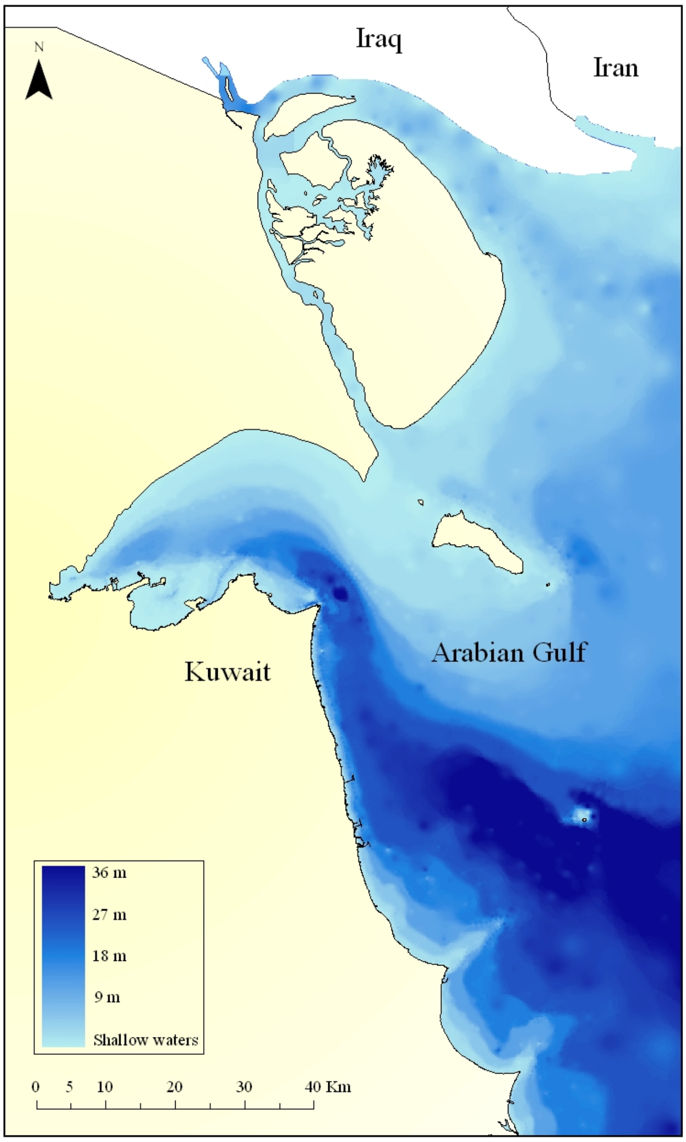

Figure 2. Illustrates the bathymetry map of Kuwait seawaters: the north area including Kuwait Bay is shallow, except the southeastern Kuwait Bay. The south waters are mostly deeper than 15 m. The digital bathymetry map was digitized based on nine detailed hardcopy bathymetry maps of Kuwait (at scale of 1:50,000) produced by the Defense Ministry of Kuwait (1995).

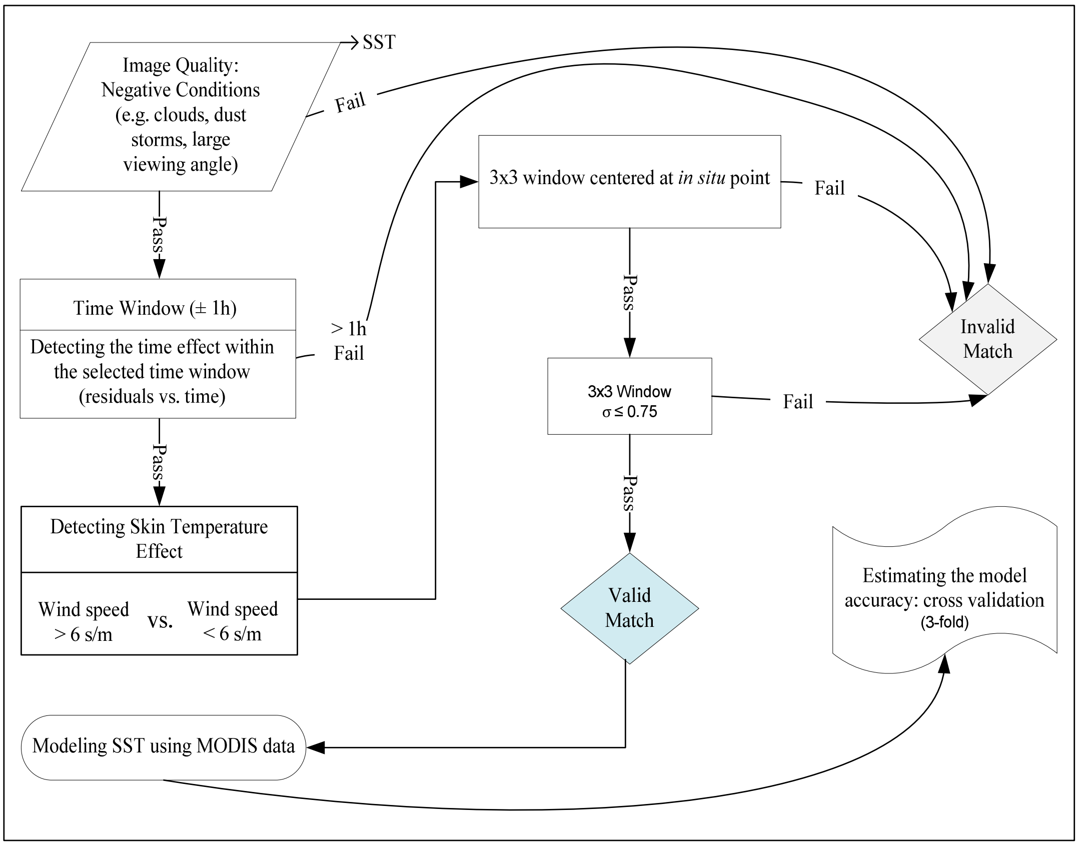

Figure 3. Illustrates the satellite images and *in situ* measurements matchup processes.

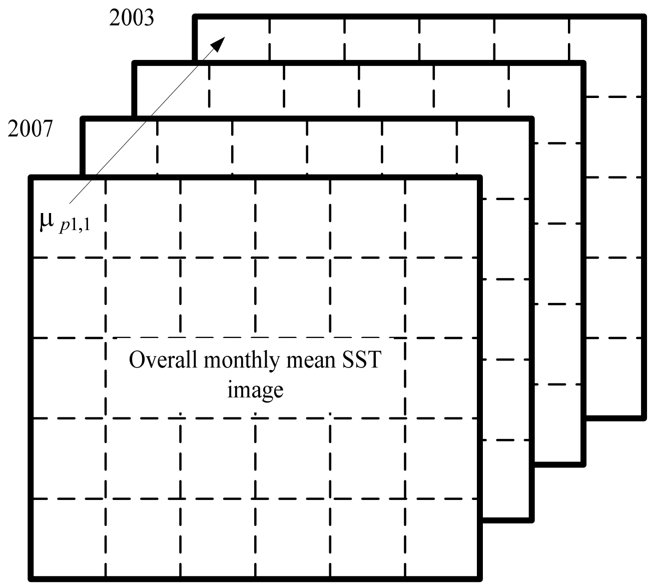

Figure 4. Illustrates an explanation of calculating the overall monthly mean SST of each calendar month.

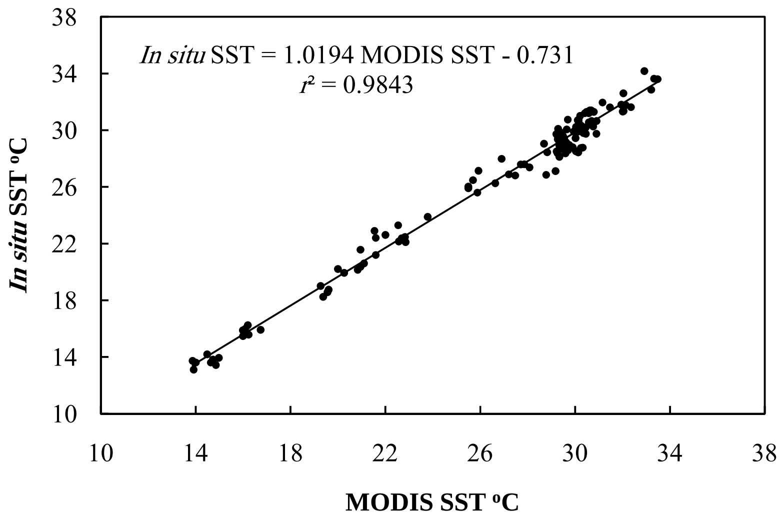

Figure 5. *In situ* SST measurements exhibited a significant relationship with MODIS SST data (r^2 = 0.98, n= 118, RMSE= 0.7 ^{o}C).

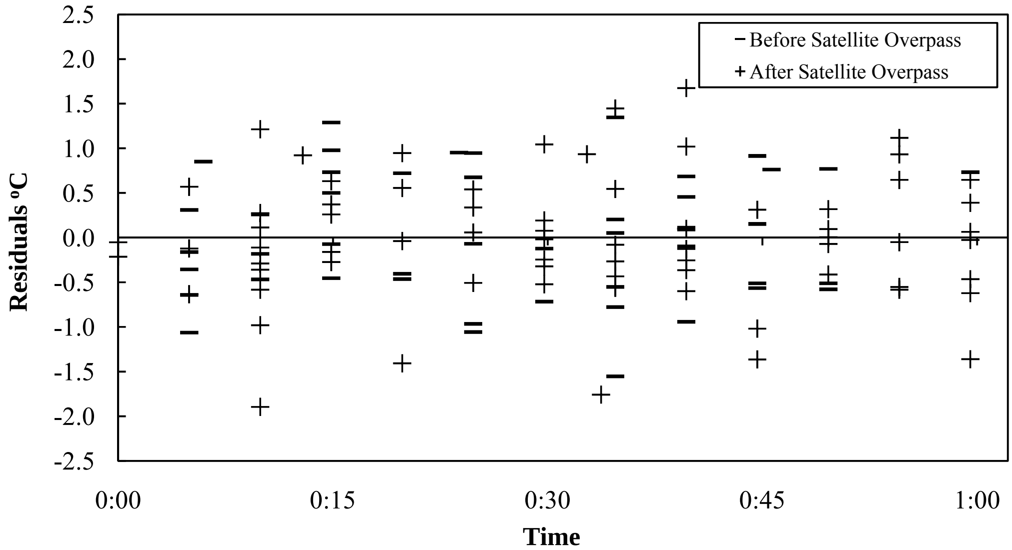

Figure 6. Shows the regression residuals of the Kuwait SST model derived from the MODIS SST ocean product over the selected time window (± 1-h). The distribution of residuals indicates that the errors do not vary with time. The minus (-) sign illustrates the *in situ* point taken before the satellite overpass, while the plus (+) sign illustrates the *in situ* point taken after the satellite overpass. The residuals are randomly distributed over the selected time window.

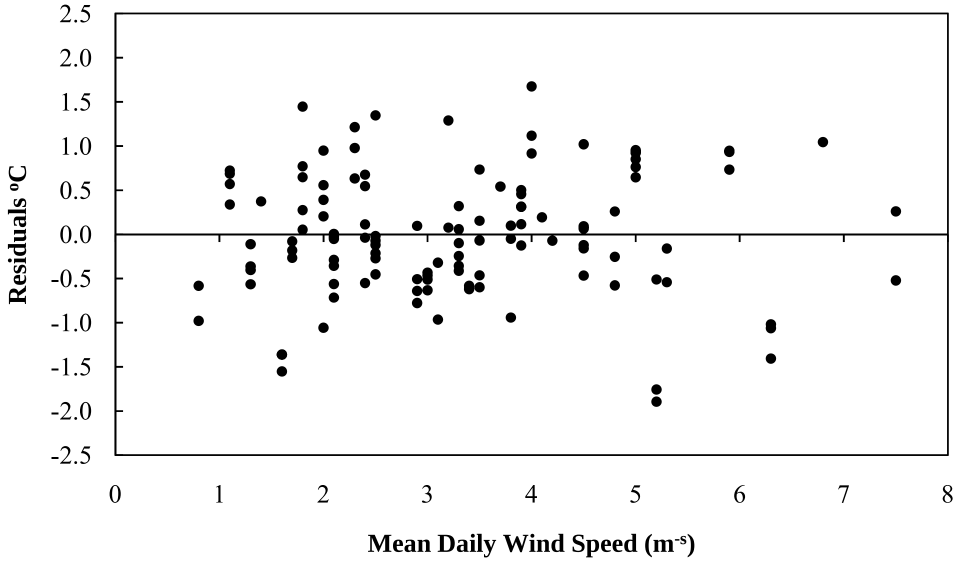

Figure 7. Shows the regression residuals of the Kuwait SST model derived from the MODIS SST ocean product against the average daily wind speed. The distribution of residuals indicates that the errors do not vary as the wind speed changes. The residuals are randomly distributed over the different wind speeds. The distribution of the residuals indicates the *in situ* data were not matched with the MODIS SST data under the skin temperature effect.

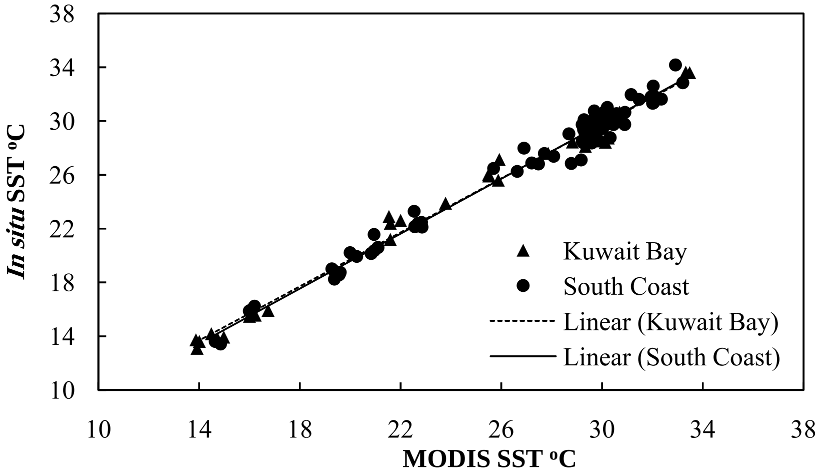

Figure 8. The visual test, pre-dummy variable analysis, illustrating a difference between the fitted line of Kuwait Bay data (*in situ* SST versus MODIS SST) and the fitted line of South Coast data (*in situ* SST versus MODIS SST). The dummy variable analysis indicated that this difference was not significant, and therefore, the SST model is was spatially constant over the study area.

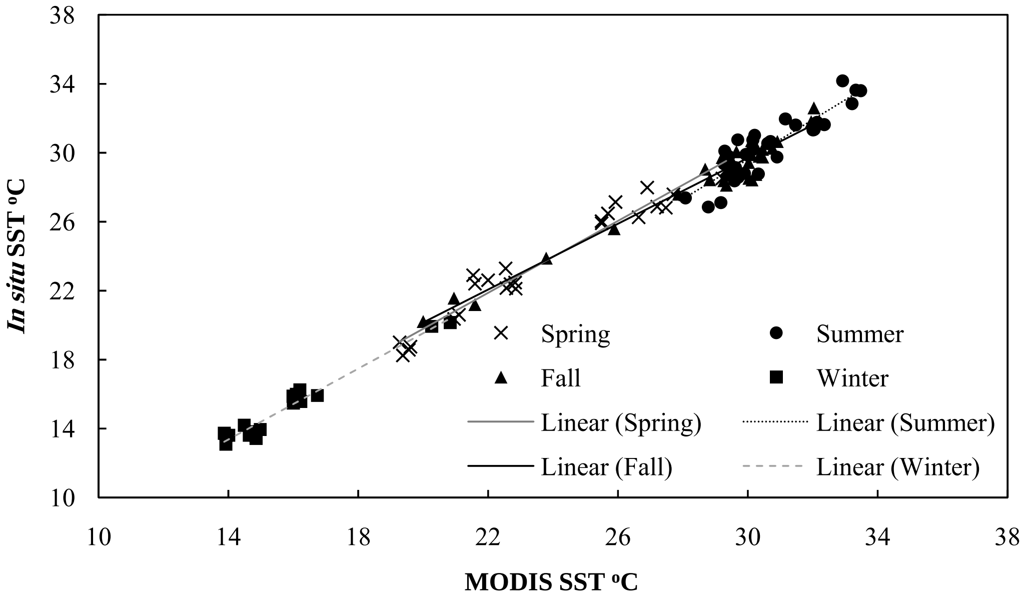

Figure 9. The visual test, pre-dummy variable analysis, illustrating the relationship of *in situ* SST and MODIS SST across the four seasons. The dummy variable analysis indicated that the SST model was constant across the four seasons.

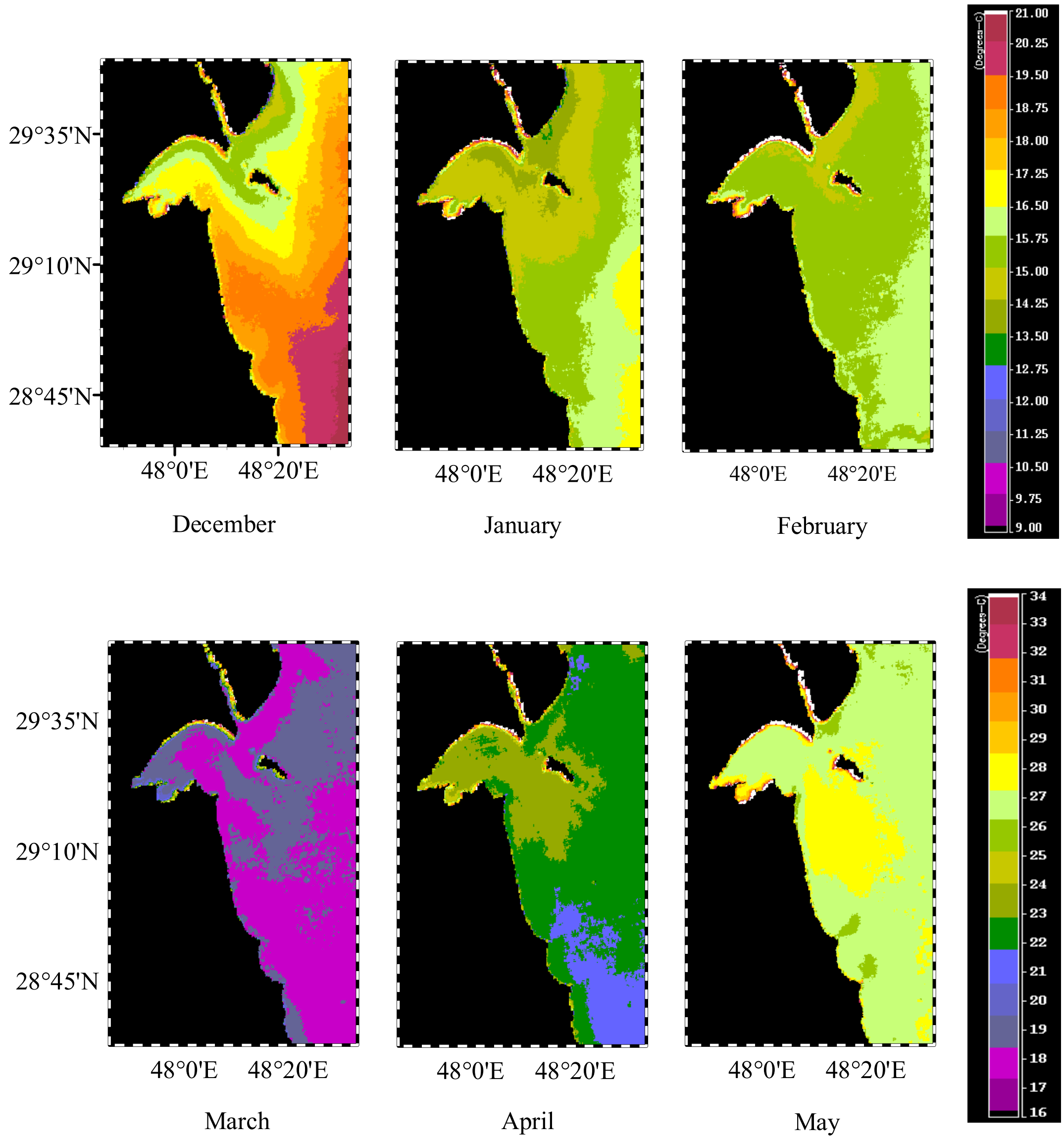

Figure 10. Overall monthly mean Kuwait SST derived from MODIS SST data. Northern Kuwait's waters had lower SSTs comparing with south waters, especially south offshore waters. This spatial arrangement was constant in the winter, middle and later summer and fall, whereas in spring, especially in March and April, this distribution was totally reversed. May and June seemed to be a transition period between the two patterns. Note that SST of Kuwait waters was affected by coastal morphology and water depths that contributed to their distinct spatial patterns in Kuwait Bay and south coast near the two headlands compared to the other areas.

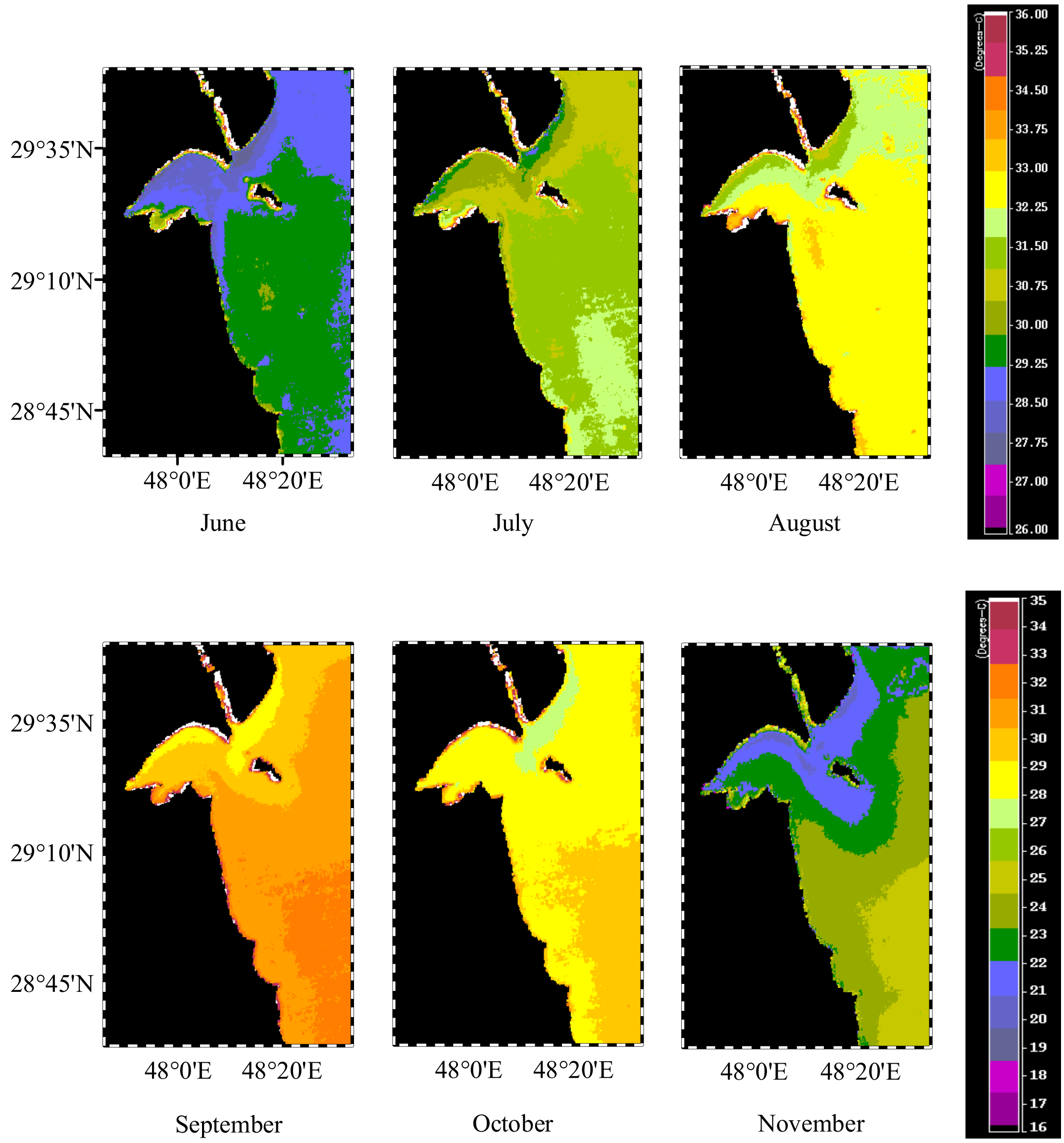

Figure 10 (continued)

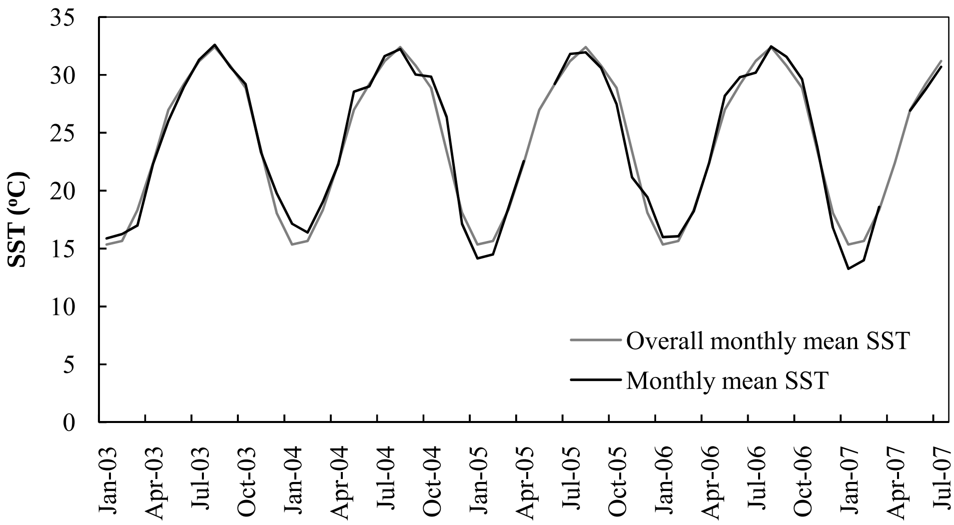

Figure 11. Illustrates the difference between the monthly mean SST of Kuwait waters (January 2003 -July 2007) and the overall monthly mean SST. Most monthly means have a bias from the overall monthly mean < ±1 ^{o}C.

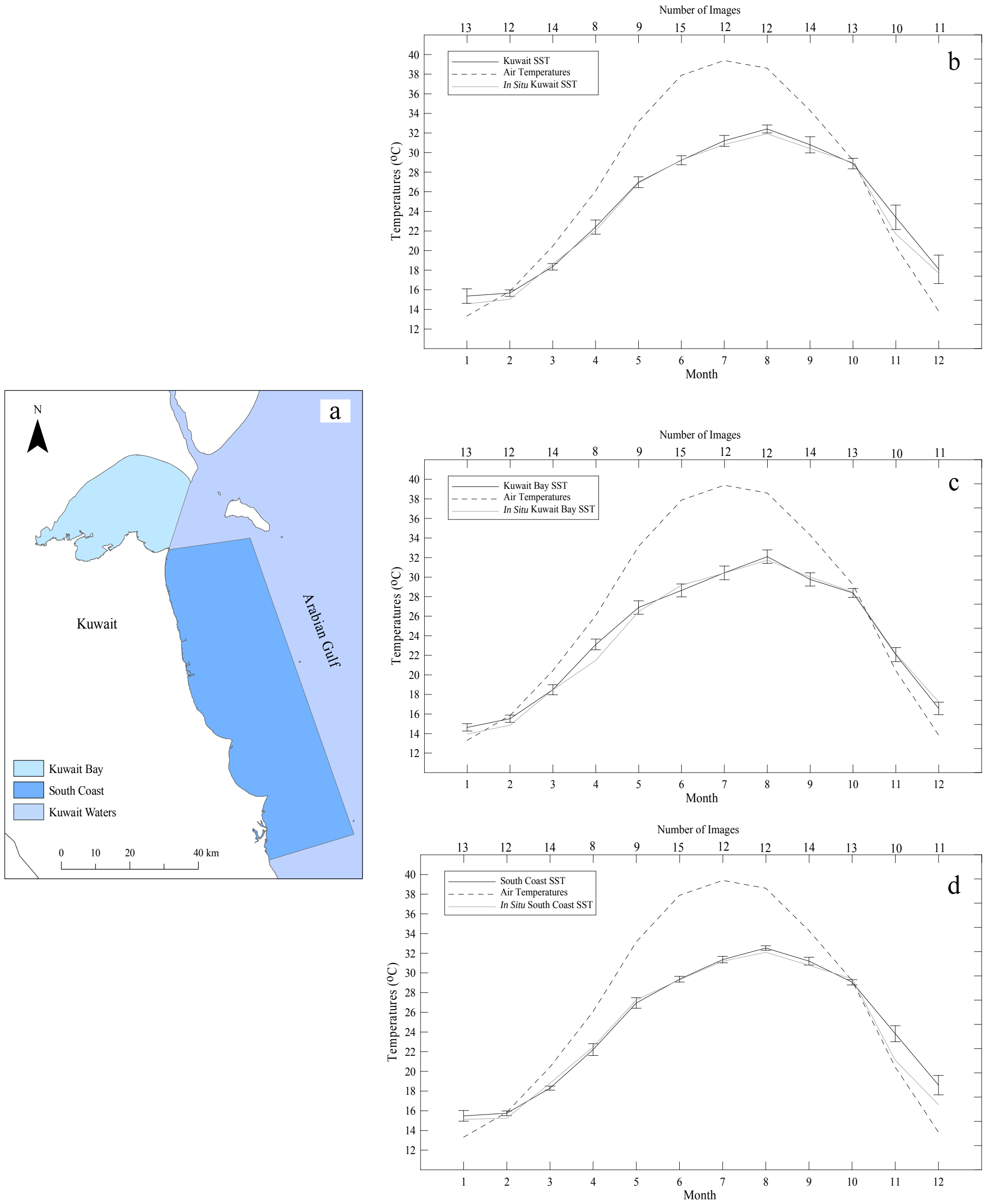

Figure 12. a) Shows the geographic limits used to specify the overall monthly mean SST of Kuwait Bay, South Coast, and the studied portion of Kuwait's territorial waters. b) Shows the overall temporal distribution of SST within Kuwait waters. The highest overall mean SST was in August (32.4 ^{o}C). c) Shows the overall temporal distribution of SST within Kuwait Bay. The highest overall mean SST was 32.1 ^{o}C (August). d) Shows the overall temporal distribution of SST within the South Coast. The highest overall mean SDD was 32.5 ^{o}C (August).

Chapter 3

Modeling Kuwait Seawater Clarity: A Spatial-Temporal Study Using Remote Sensing and GIS

Abstract

Kuwait water clarity is an important water quality indicator that influences the entire Kuwait coastal ecosystem. The spatial and temporal distributions of this important water characteristic should be well understood to obtain a better knowledge about this productive coastal environment. The aim of this project was therefore to study the spatial and temporal distributions of Kuwait Secchi Disk Depth (SDD), a water clarity measure, using Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and Moderate Resolution Imaging Spectroradiometer (MODIS) data collected from November 1998 to October 2004 and January 2003 to June 2007, respectively.

Kuwait SDD was measured through two steps: first, computing the diffuse light attenuation coefficient at 490 nm, $K_d(490)$, and 488 nm, $K_d(488)$, derived from SeaWiFS and MODIS, respectively, using a semi-analytical algorithm; second, establishing two SDD models based on the empirical relationship of $K_d(490)$ and $K_d(488)$ with *in situ* SDD data that I collected from the study area during June 2007 and those collected by the Kuwait Environmental Public Authority (EPA) between November 1998 and June 2007. $K_d(490)$ and $K_d(488)$ showed a significant relationship with *in situ* SDD data (r^2= 0.67 and r^2= 0.68, respectively). Kuwait SDD derived from SeaWiFS and MODIS images showed that Kuwait water clarity increased from north to south and from inshore to offshore. This spatial pattern was

mainly attributed to three factors: the Shatt Al-Arab discharge, water circulation, and coastal currents. The Kuwait SDD increased from January to May and, then, started to decrease until November with a minor decrease in April and a minor increase in December. The temporal variations in Kuwait water clarity were influenced by the Shatt Al-Arab discharge variation. The SeaWiFS and MODIS data compared to *in situ* measurements provided a comprehensive view of Kuwait SDD that improved the estimation of overall SSD mean within Kuwait waters. Thus, I recommend involving this method in monitoring Kuwait coastal environments.

Introduction

The Kuwait coastal environments in the northwestern Arabian (Persian) Gulf are very productive environments that provide the State of Kuwait with food, freshwater (by desalination), and electrical power. Kuwait seawaters are rich in a diversity of fishery species that provides about 40 to 50% of the country's seafood demand (Al-Yamani *et al*., 2004). Kuwait relies on desalination stations and power plants along the coast for its freshwater supply and electrical power. During the last three decades, Kuwait's marine environments were impacted by critical factors (consequences of three major wars, destruction of Iraqi marshes, reduction of the Shatt Al-Arab discharge, and increased anthropogenic activities) that threatened the sustainability of these environments. Given the extreme importance of these productive environments, and all factors threatening their sustainability, a synoptic environmental monitoring program needed to be developed and implemented.

An efficient environmental program should be designed to comprehensively monitor the water quality characteristics that affect all aspects of the marine environment. One of the most basic and yet important water quality indicators is water clarity that controls the light intensity available for marine organisms (Segar, 1998). Traditional methods of collecting water clarity data are logistically challenging and do not provide a high spatial-temporal synoptic perspective of the water clarity. Thus, methodologies providing an accurate comprehensive perspective of the Kuwait seawater clarity, such as the integration of ground truth and remotely sensed data, are greatly needed (Al-Yamani *et al*., 2004; Nezlin *et al*., 2007).

Water clarity is controlled by several factors, such as phytoplankton abundance, suspended sediments, detritus, and dissolved organic matter that impede light penetration by absorption, diffusion, and reflectance (Gower, 2006; Miller *et al*., 2005; Ustin, 2004). In 1866, an Italian scholar named Angelo Secchi created a disk to measure the depth of light penetration in water as a tool for measuring water clarity. Thereafter, this tool became very popular in scientific communities because of its simplicity and low cost. The tool remains one of the fundamental instruments to study water clarity in spite of emerging new instruments (Holmes, 1970; Preisendorfer, 1986).

Preisendorfer (1986) developed an equation to derive Secchi Disk Depth (SDD) using diffuse light attenuation, K_d. Megard and Berman (1989) examined the correlation between marine algae, SDD, and K_d in the southeastern Mediterranean Sea, and concluded that the secchi disk provides accurate measurements of water clarity comparable with measurements derived by K_d. Sanden and Hakansson (1996) found a clear inverse relationship between chlorophyll concentrations, an indicator of phytoplankton biomass, and SDD over a long term study period in the Baltic Sea.

Factors influencing water clarity in the Arabian Gulf have been addressed in many studies. Sohrabpour *et al*. (2004) studied sediment samples near Bushier Nuclear Power Plant to provide an important report about the environmental situation of the area before the establishment of the nuclear power plant. Al-Ghadban and El-Sammak (2005) examined the spatial distribution of suspended sediments in Kuwait Bay at 12 sites in 1989 and 1992 and observed that suspended sediment concentrations in Kuwait Bay dramatically increased after the Gulf War II. Beg and Al-Ghadban (2003) observed the Kuwait coastal environmental response to the drainage of Iraqi marshes by examining the quality of sediments at 20 sites in the northern part of Kuwait seawaters and found that their samples were characterized by toxicity.

Several studies in the Arabian Gulf focused on water clarity and its role in the marine environment. Shriadah and Al-Ghais (1999) studied water clarity and other seawater characteristics of the United Arab Emirates. Abou-Seedo *et al*. (1990) found that fish abundance and distribution at two study sites in Kuwait Bay were highly related to the water clarity variation.

The collection of *in situ* data from the marine environment can present many logistical challenges: marine studies relying merely on *in situ* measurements are handicapped by the inability to capture field data in a timely, spatially dense, and geographically referenced format. In recent years, oceanographers and marine biologists have begun using remotely sensed imagery to study the water quality of ocean and coastal environments (Gower, 2006). Remotely sensed data have added valuable contributions in understanding the aquatic ecosystems. They provide comprehensive perspectives of fundamental aquatic characteristics, such as water clarity. Remotely sensed methodologies used to detect these components were developed based on physical, statistical, and environmental factors.

Water clarity can be remotely estimated using the light diffuse attenuation coefficient at ~ 490 nm, $K_d(490)$. Dareckia and Stramski (2004) found that the empirical $K_d(490)$ and $K_d(488)$ (default level 2 products) of Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and Moderate Resolution Imaging Spectroradiometer (MODIS), respectively, showed acceptable accuracy in the Baltic Sea. Chen *et al*. (2007) stated that the semi-analytical algorithm is more accurate than the empirical method, default level 2 product, in detecting water clarity in Case 2 environments, such as Tama Bay, where the optical appearance of waters is associated with components such as detritus and colored dissolved organic matter (CDOM) rather than associating with only phytoplankton as in open oceans, Case 1 waters (Miller *et al*., 2005). Pierson *et al*. (2008) modeled photosynthetically available radiation, K_d (PAR), in the Baltic Sea using $K_d(490)$ derived from SeaWiFS.

Marine studies relying on remotely sensed data in the Arabian Gulf, especially in Kuwait waters, are not common although the interest in using remotely sensed data in this region has increased in recent years. Al-Ghadban (2004) used Landsat and

SPOT remotely sensed data to assess suspended sediment distributions in 1989 and 1993 using 13 sites in Kuwait Bay. He stated that the study can be considered as an example of using remote sensing in coastal studies in the northern part of the Arabian Gulf. Nezlin *et al*. (2007) studied chlorophyll concentrations, K_d (PAR), and sea surface temperature (SST) of the Arabian Gulf region at global resolution (9 and 4.5 km) using SeaWiFS, Advanced Very High Resolution Radiometer (AVHRR), and MODIS from September 1997 to May 2006. They stated that future marine studies in the Arabian Gulf using remotely sensed data need to be validated using ground truth data. Al-Yamani *et al*. (2004) also believed that there is a need to establish relationships between *in situ* measurements and remotely sensed data so that a better understanding of this particular region of the Arabian Gulf can be achieved.

Study Goal

Previous oceanographic studies in the northwestern Arabian Gulf have been limited by the lack of multitemporal analysis and use of remote sensing technologies, especially the integration of *in situ* measurements with remotely sensed data (Al-Yamani *et al*., 2004; Nezlin *et al*., 2007). As a consequence, the spatial-temporal variability of important seawater characteristics, such as water clarity, in this region remains unknown, or at least, their estimation remains scientifically insufficient. To my knowledge, empirical remotely sensed models measuring water clarity within the northwestern Arabian Gulf waters have not been established. The goals of this study were to: 1) develop two empirical models for estimating Kuwait water clarity using the semi-analytical derived K_d(490) and K_d(488) of Sea-viewing Wide Field-of-view

Sensor (SeaWiFS) and Moderate Resolution Imaging Spectroradiometer (MODIS), respectively (Feldman and McClain, 2008a, b) ; 2) map the spatial and temporal distributions of Kuwait water clarity for the period of November 1998 to June 2007; and 3) assess the interrelationships between water clarity and SST, and chlorophyll concentrations within Kuwait seawaters.

Study Area

The study area, located in the northwestern part of the Arabian Gulf in Kuwait seawaters, lies within the geographic coordinates of 28^{o} 32’ to 29^{o} 50’ N and from 47^{o} 34’ to 48^{o} 40’ E (Figure 1). This area was selected because of availability of seawater quality data that have been collected on a relatively consistent basis for 20 years, and because of my familiarity with the geography of the region. The coastline of Kuwait is about 350 km long including Kuwait Bay that is the most vital area in the country where the urban, commercial and industrial sectors are concentrated (Al-Bakri and Kittaneh, 1998).

Kuwait seawaters are greatly influenced by the fresh waters coming into the Gulf from the Shatt Al-Arab, which is the product of three major rivers: the Euphrates, Tigris and Karun Rivers. The Shatt Al-Arab discharge plays a valuable role in decreasing the salinity and supporting Kuwait seawaters with nutrients that makes these environments optimum habitats from many marine organisms: the spatial and temporal distributions of Kuwait seawater characteristics, such as salinity and nutrients are clearly associated with the Shatt Al-Arab discharge (Al-Yamani *et al.*, 2004). Unfortunately, information about the Shatt Al-Arab during the last three decades is virtually unavailable to the scientific community due to the continuous political conflicts in this region (Al-Hilli *et al*., 2009; Al-Yamani, 2008; Al-Yamani *et al*., 2004).

The estimated Shatt Al-Arab discharge is about 1456 m^3 s^{-1} (Al-Yamani *et al*., 2004). The current Shatt Al-Arab discharge, however, must be critically reduced to unknown rates due to the massive dam projects built on the Euphrates, Tigris, and Karun Rivers that feed the Shatt Al-Arab River (Al-Yamani, 2008). Pre-1980 studies revealed that the Shatt Al-Arab inflow increases during December through June, with maximum discharge occurred in May, because of heavy rainfall in the winter and melting of snow in Turkey, Syria, Iraq and Iran in the spring (Al-Yamani *et al*., 2004). The Shatt Al-Arab discharge is now expected to increase in winter due to the upstream water regulation procedures that almost completely restrict the spring flood for drinking and irrigation demand during dried months and release the river flow in the winter to generate hydro-electrical power (Kangi and Heidari, 2008; Lapshin, 2000; Rahi and Halihan, 2009). Al-Yamani (2008) states that winter rainfall over the Shatt Al-Arab and adjacent areas contributes to increasing the Shatt Al-Arab discharge in January and February, whereas the spring flood increases the Shatt Al-Arab discharge in May.

Kuwait seawater including Kuwait Bay is influenced by the wind-dominant counterclockwise circulation in the northwestern Gulf: some local circulations are also present (Al-Yamani *et al*., 2004). The water currents in the Bay are classified into two zones, eastern and western. The eastern zone has a relatively higher current velocity and is affected by water inflow from the Shatt Al-Arab River that is characterized by lower salinity and temperature, whereas the western zone has less current velocity and is characterized by increased temperature, salinity, and suspended sediments (Al-Ghadban and El-Sammak, 2005).

Climatic conditions are an important influence on the marine environments of Kuwait. Wind speed and direction affect the currents and circulations of Kuwait seawaters (Reynolds, 2002). The northwestern wind is the dominant wind in the northwestern Arabian Gulf that increases in the summer months and decreases in the spring months. The southeastern wind is the second dominant wind in the region that usually occurs in the spring with minimum occurrence in the summer. Dust storms can occur any time of the year, but they usually occur in June and July (Al-Yamani *et al*., 2004). Dust storms are an important source of sediments and nutrients that sometimes change the Kuwait seawaters' properties (Rao and Al-Yamani, 1999).

Methodology

In Situ Measurements

The Environmental Public Authority (EPA) of Kuwait has been collecting seawater samples at 13 locations in the waters of Kuwait since 1985. The selection of the geographic locations of the 13 sample sites was determined by the EPA based on their concerns about water conditions near the nation's electrical power and desalination plants and other vital sites. The *in situ* data collection and laboratory analysis of EPA were performed according to the guidelines published in the Manual of Oceanographic Observations and Pollutant Analyses Methods, ROPME 1999 (MOOPAM).

Two EPA measurement of particular interest to this study are chlorophyll concentrations collected from November 1998 to December 2006 and SDD collected from November 1998 through June 2007 (EPA, 2007). This time period was selected to match satellite data availability. In addition to the EPA measurements, I used SDD data that I collected from the Kuwait waters in June 22, 2007 at eight offshore sites using a secchi disk (Figure 1). The selected date was based on the weather and sea conditions most suitable for safe navigation and taking measurements in these months.

Remotely Sensed Data

Satellite Imagery

SeaWiFS and MODIS (Aqua) images were used to model the spatial and temporal distribution of Kuwait water clarity. SeaWiFS and MODIS (~ 1 km) images collected from November 1998 to October 2004 and January 2003 to June 2007, respectively, were downloaded from the Ocean Color Web Database (Feldman and McClain, 2008a, b). SeaWiFS images post October 2004 were disregarded because they are only available at global resolution (4.4 km) for the studied region. Thus, SeaWiFS and MODIS images should be used as complements to each other for long term studies in this region. To ensure image quality, images with large viewing angle and images acquired during dust storms were disregarded. The negative atmospheric conditions were assessed using available metrological data from the Kuwait

International Airport (Directorate of Civil Aviation, 2007), about 30 km off the study area, and also by visual assessment of the imagery using natural color band combinations.

Image processing

SeaWiFS and MODIS level 1-A remotely sensed data were processed to level 2 to obtain $K_d(490)$ and $K_d(488)$, respectively, using the SeaWiFS Data Analysis System (SeaDAS 5.3) software (Baith *et al*., 2001). The images were processed using the SeaDAS default Level 2 process algorithm (Feldman and McClain, 2009). The $K_d(490)$ and $K_d(488)$ were calculated using the semi-analytical algorithm proposed by Lee *et al.* (2005a) that calculates the backscattering and absorption coefficients from the remotely sensed reflectance measurements and use them in estimating $K_d(490)$ or $K_d(488)$. This algorithm is the most efficient method to derive $K_d(490)$ and $K_d(488)$ in Case 2 waters (Chen *et al*., 2007), such as Kuwait waters, where the optical appearance of waters is associated with components such as detritus and CDOM rather than with only phytoplankton as in open oceans, Case 1 waters (Miller *et al*., 2005). The derived $K_d(490)$ and $K_d(488)$ ocean products were used to model Kuwait water clarity. The images were geo-registered to a common projection to compute the overall monthly mean of Kuwait water clarity discussed in the subsequent sections.

Satellite-*in situ* matching

A time window of ±3h was used to match SDD measurements with SeaWiFS and MODIS images. The relationship between matched data was tested for constancy over time to ensure the adequacy of the selected time window. The images were matched with *in situ* measurements using the mean of a 3x3 pixel array to take into account errors in satellite navigation, and errors due to geophysical variability (Bailey and Werdell, 2006). Arrays with five or more invalid (masked) pixels were excluded from the analysis. Pixels were considered invalid due to atmospheric correction failure, large solar and satellite angles, sensor errors, and mixed pixels (inland-water pixels) (Hu *et al*., 2000). Pixels covering shallower waters (< 2 m of depth) were also excluded from the analysis to minimize the bottom reflectance effect (Lodhi, 2002). Seawater depths were assessed using a bathymetry map digitized based on nine detailed hardcopy bathymetry maps of Kuwait (at scale of 1:50,000) produced by the Defense Ministry of Kuwait (1995) (Appendix, Figure B&C).

The mean of the 3x3 pixel array was computed using a filtering method described by Bailey and Werdell (2006) to screen the outliers. The equation of the filtered mean is:

$$\text{Filtered Mean} = \frac{\sum_i (1.5*\sigma - \bar{X}) < X_i < (1.5*\sigma + \bar{X})}{N} \qquad \text{Equation.1}$$

where $\bar{X}$ and σ are the mean and standard deviation, respectively, of the nine pixel values extracted from each 3x3 pixel box, and *N* is the number of pixel values within $\pm\ 1.5*\sigma$ from the mean of the 3x3 pixel array. The filtered mean, in other words, is the mean of pixel values that occur within $\pm\ 1.5*\sigma$ of the unfiltered mean. Filtered arrays with a coefficient of variation (CV) exceeding 0.4 were excluded. The selected

CV value was based on the value used by Chen *et al*. (2007). Figure D in the appendix summarizes the satellite- *in situ* matchup processes.

Data Analysis

Comparing in situ SDD to satellite K_d(490) and K_d(488)

The relationship between SDD and $K_d(\lambda)$ at 490 and 488 nm was modeled using power regression, also called log-log regression (Hocking, 2003; Motulsky and Christopoulos, 2004). The spatial constancy of the two models (SDD- K_d(490) and SDD- K_d(488)) was tested using dummy variable analysis (Montgomery and Peck, 2001; Silk, 1976). The analysis was performed to statistically detect whether the relationship of *in situ* SDD with K_d(490), and with K_d(488) in Kuwait Bay differs from that of the south coast in respect to the model's slope and intercept. The relationship of SDD with K_d(490), and with K_d(488) was tested in the Kuwait Bay and the south coast areas because the two are spatially distinct in terms of their environmental and anthropogenic aspects (e.g., water depths and domestic and industrial waste) that might affect the models' spatial constancy. The regression equation using dummy variable is:

$$\log(SDD) = \beta_0 + \beta_1 \log\left(K_\mathrm{d}(\lambda)\right) + \beta_2 L + \beta_3 K_\mathrm{d}(\lambda) L \qquad \text{Equation. 2}$$

where β_0 is the y-intercept, β_1 is the slope, and β_2 and β_3 are the change in the y-intercept and slope from Kuwait Bay to south coast, respectively. $K_\mathrm{d}(\lambda)$ is the diffuse light attenuation coefficient at 490 nm for SDD-SeaWiFS analysis and at 488 nm for SDD-MODIS analysis. L is the dummy variable that is set equal to 0 when comparing

SDD with $K_{\mathrm{d}}(\lambda)$ in Kuwait Bay, and 1 when comparing SDD with $K_{\mathrm{d}}(\lambda)$ in Kuwait's southern coastal waters. Thus, the previous equation can be divided into two parts based on the dummy variable (L):

$$\log(SDD) = \begin{cases} \beta_0 + \beta_1 \log(K_{\mathrm{d}}(\lambda)) & \text{If } L = 0 \quad \text{Equation. 3a} \\ (\beta_0 + \beta_2) + \log(K_{\mathrm{d}}(\lambda))(\beta_1 + \beta_3) & \text{If } L = 1 \quad \text{Equation. 3b} \end{cases}$$

The model's spatial constancy was tested based on β_2 and β_3 at the 0.05 level of significance using ANOVA.

The accuracy of the two Kuwait SDD models derived from $K_{\mathrm{d}}(490)$ and $K_{\mathrm{d}}(488)$, respectively, were tested using mean and median predicted SDD-to-*in situ* SDD ratio, mean and median absolute percent difference (PD), and root mean square error (RMSE). The mean and median predicted SDD-to-*in situ* SDD ratio is used to measure the overall model bias, whereas the mean and median PD is used to measure the model uncertainty (Bailey and Werdell, 2006; Chen *et al.*, 2007). The PD is calculated as:

$$\mathrm{PD}_i = 100 * \frac{|\widehat{SDD_i} - SDD_i|}{SDD_i} \qquad \text{Equation. 4}$$

where $\widehat{SDD}$ is the predicted value derived from $K_{\mathrm{d}}(490)$ and $K_{\mathrm{d}}(488)$, and *SDD* is the *in situ* measurement.

The Kuwait SDD models were tested in a simulated environment using leave-one-out cross validation in which the models were derived while holding out one observation that was later used to test the model's ability to predict the values of the one observation not used in creating the model. This process was repeated until all observations were withheld from the model-building process (Camstra and Boomsma, 1992; Jonathan *et al*., 2000).

Calculating the overall monthly mean of Kuwait water clarity

K_d(490) and K_d(488) images of SeaWiFS and MODIS, respectively, acquired during the study period were selected based on the image quality criteria discussed earlier to calculate Kuwait water clarity using the two SDD models of Kuwait. The modeled SDD images were used to calculate the overall monthly mean of Kuwait water clarity. The overall monthly mean was computed as:

$$\mu_{Pij} = \frac{\sum_{I=1}^{n} PV_{Pij}}{n} \qquad \text{Equation. 5}$$

where μ_{Pij} is the mean of the pixel at row $_i$ and column $_j$, *I* is an SDD image, n is the number of images, and PV_{Pij} is the value of Pij (Appendix, Figure E).

The overall monthly mean images of Kuwait water clarity resulted from Equation.4 were imported into a GIS system to exclude SDD of shallow waters and calculate the SDD of Kuwait Bay and south coast areas (Appendix, Figure F). SDD data derived from the overall monthly mean images of Kuwait water clarity were compared with the overall monthly mean of *in situ* chlorophyll concentrations and MODIS SST data described in chapter 2.

Result

Comparing *in situ* SDD to SeaWiFS K_d(490) and MODIS K_d(488)

In situ SDD-SeaWiFS K_d(490)

A total of 80 *in situ* SDD points were matched with K_d(490) images acquired from November 1998 to October 2004 based on the quality criteria described earlier: 48 of them were in Kuwait Bay and 32 of them were in the south coast. Station Z02 was excluded from the analysis because of its adjacency to the shore (Figure 1). The matched *in situ* points were distributed over the four seasons as follows: 9 in spring, 10 in summer, 13 in fall, and 48 in winter.

The relationship between *in situ* SDD and K_d(490) was significant (SDD = $0.5368*K_d(490)^{-1.27}$, 0.5 m < SDD < 7.60 m, $r^2 = 0.67$) (Figure 2a). The mean and median predicted SDD-to-*in situ* SDD ratio and PD were 1.06, 1.03, 28.07%, and 22.98%, respectively. The regression RMSE was 0.75 m, whereas the RMSE derived from the cross validation analysis was 0.77 m based on an *in situ* range from 0.5 to 7.60 m. These values indicated that the SDD model can be used to detect water clarity in most Kuwait waters across the year.

The regression residuals over the selected time window were almost randomly distributed, except those data matched within ± 2-3h that seemed to have lower residuals (Figure 3a). This pattern was perhaps due to the frequency of occurrence of the data over the selected time. The distribution of the regression residuals proved the suitability of the selected time window in matching *in situ* SDD with K_d(490) since the residuals were not ascending toward the end of the time window. The SDD model was spatially constant: the dummy variable analysis indicated that the relationship between *in situ* SDD and $K_d(490)$ in Kuwait Bay and south coast was not significantly different (P-value of β_2 =0.082 and P-value of β_3= 0.246) (Appendix, Figure Ga).

In situ SDD-MODIS $K_d(488)$

A total of 66 *in situ* SDD points were matched with $K_d(488)$ images acquired from January 2003 to June 2007 based on the quality criteria described earlier: 37 matched *in situ* points were in Kuwait Bay, 27 matched *in situ* points were in the south coast, and 2 matched *in situ* points were from offshore sites. The matched *in situ* points were distributed over the four seasons as follows: 4 in spring, 16 in summer, 21 in fall, and 25 in winter.

The relationship between *in situ* SDD and $K_d(488)$ was significant (SDD = $0.3591*K_d(488)^{-1.672}$, 0.55 m < SDD < 10.50 m, $r^2 = 0.68$) (Figure 2b). The mean and median predicted SDD-to-*in situ* SDD ratio and mean and median PD were 1.07, 0.96, 30.02%, and 20.98%, respectively. The regression RMSE was 1.08 m, whereas the RMSE derived from the cross validation analysis was 1.10 m based on *in situ* range from 0.55 to 10.50 m. These values indicated that the SDD model can be used to detect water clarity in most Kuwait waters across the year (Table 1).

The regression residuals over the selected time window illustrated a reasonable random distribution, except those data matched within ± ~ 2-3h that seemed to have lower residuals (Figure 3b). This pattern was perhaps due to the frequency of occurrence of the data over the selected time. The distribution of the regression residuals indicated the selected time for matching *in situ* SDD with

K_d(488) was reasonable: the residuals were not ascending toward the end of the time window. The SDD model was spatially constant: the dummy variable analysis revealed that the relationship between *in situ* SDD and K_d(488) in Kuwait Bay and the south coast was not significantly different (P-value of β_2 =0.0769 and P-value of β_3= 0.724) (Appendix, Figure Gb).

SDD image series analysis

The overall monthly mean of Kuwait SDD images illustrated distinct spatial and temporal distributions. Kuwait water clarity increased from north to south and from inshore to offshore (Figure 4). This spatial pattern was constant across the year. The Kuwait SDD increased from January (2.7 m) to May (4.4 m) and, then, started decreasing until November (2.7 m) (Table 2). The Kuwait SDD exhibited a minor decrease in April and a minor increase in December. Kuwait water clarity exhibited the highest spatial variability in June (the standard deviation was 3.08 m). The overall monthly mean trend of *in situ* SDD and SDD images disagreed in the months of February, September, October, and December (Figure 5a &b). The lowest monthly mean of the Kuwait SDD of 1.9 m occurred in January 1999, whereas the highest monthly mean of the Kuwait SDD of 5.9 m occurred May 1999. Figure 6 showed the difference between the monthly mean SDD and overall monthly mean SDD of Kuwait waters following the idea used by Chen *et al*. (2007).

The water clarity in Kuwait Bay was very low compared to other Kuwait waters. In general, the center of the Bay and its southern entrance exhibited the highest SDD in the bay in all months (Figure 7). The Kuwait Bay SDD temporal variation was different from the general temporal distribution of the Kuwait SDD although the highest SDD in Kuwait Bay was observed in May (Figure 5c). The overall monthly mean of Kuwait Bay SDD ranged from 1.0 m in April to 1.3 m in May (Table 2). The water clarity in Kuwait Bay exhibited the highest spatial variability in August (the standard deviation was 3.34 m).

The south coast waters had higher SDD values comparing to those in Kuwait Bay. The Kuwait southeastern waters had the highest SDD values in all months. The SDD temporal variation in the south coast followed the general temporal variation of Kuwait SDD, except that the south coast SDD continued increasing until June (Figure 5d). The overall monthly mean of the south coast SDD ranged from 3.1 m in November to 5.1 m in June with the highest spatial variability in May (the standard deviation was 2.56 m) (Table 2).

The water clarity of Kuwait temporally covaried with chlorophyll concentrations. The temporal variation of Kuwait water clarity showed a distinct pattern with chlorophyll concentration variability from January to May (Figure 8a). In Kuwait Bay, the SDD decline occurring in January, March, and April was accompanied by an increase in chlorophyll concentrations, whereas the SDD increase occurring in February and May was accompanied by a chlorophyll concentration decline. Thus, the water clarity in these months was attributed in some degree to the chlorophyll concentrations, whereas the water clarity in the other months varied independently from chlorophyll variations. The water clarity in the south coast was associated with chlorophyll variability during March to July, while the water clarity for the rest of the year had no association with chlorophyll concentrations (Figure 8b).

Contrarily, the water clarity of Kuwait did not have a clear temporal association with Kuwait SST whose temporal variability was controlled by the seasonal variations of solar intensity and air temperature. The Kuwait SST images, however, served as important complementary data for detecting water movements that can effectively aid in explaining the spatial distribution of Kuwait water clarity. Such a relationship between the SST and water clarity variables was responsible for some similarities in their spatial distributions. The SDD and SST images showed that the near-shore spatial distributions of the SDD and SST of Kuwait had similar patterns, especially near the two headlands (namely from north Ras Al-Julaiah and Ras Al-Zour) in the south of Kuwait. Such patterns clearly appeared in SDD and SST images during May and June (Figure 4 & 9). Also, the spatial distribution of SDD and SST in Kuwait Bay were distinct compared to the other Kuwait waters.

Discussion

The Kuwait SDD model implications

The $K_d(490)$ and $K_d(488)$ semi-analytically derived from SeaWiFS and MODIS, respectively, were efficient in modeling water clarity within most of the Kuwait waters in all seasons. The *in situ* SDD range used to match with the $K_d(490)$ and $K_d(488)$ images presented most of the water clarity variation within Kuwait waters. This SDD range presented the water clarity variability in Kuwait Bay and the south coast, the most significant Kuwait's territorial waters. The only area that exceeded the tested SDD ranged was the offshore south and southeastern waters of Kuwait during May until July. Thus, the two SDD models presented in this project can be used to estimate water clarity within most of Kuwait waters across the year.

The Kuwait SDD model derived from SeaWiFS K_d(490) agreed with the Chen *et al*. (2007) model, semi-analytically derived from SeaWiFS K_d(490): both models have r^2 equal to 0.67 with n = 80. Chen *et al*. (2007) established the SDD model using an *in situ* SDD range (0.9 m to 8.0 m) similar to the *in situ* SDD range of the Kuwait SDD model (0.5 m to 7.6 m). The Chen *et al*. (2007) model, however, has relatively lower mean and median predicted SDD-to-*in situ* SDD ratios (1.02 and 1.00), mean and median absolute PD (16% and 14%), and RMSE (0.55 m) compared to those of the Kuwait SDD model that were 1.06, 1.03, 28%, 22% , and 0.75 m, respectively. These differences could be due to the potential difference in the distribution of *in situ* SDD data used in the two models. The general agreement between the two models indicates that the semi-analytical K_d(490) of SeaWiFS can be widely used to estimate SDD in coastal environments. Also, the semi-analytical K_d(488) of MODIS can be efficiently integrated with the SeaWiFS data in estimating SDD in coastal environments since both sensors' data are processed using similar procedures.

The two Kuwait SDD models derived from SeaWiFS and MODIS can be useful for many coastal applications including fisheries and coastal marine ecology applications (e.g., Abou-Seedo *et al*., 1990; Brager *et al*., 2003; Laird, 2006). Also, the Kuwait SDD models can efficiently be used in monitoring Kuwait water clarity.

The modeled SDD data derived from SeaWiFS and MODIS provide a comprehensive spatial-temporal coverage of Kuwait water clarity that cannot be provided by *in situ* measurements. The comprehensive monitoring of Kuwait water clarity can provide a better understanding of this critical water characteristic that is linked to important abiotic and biotic components, such as turbidity and chlorophyll concentrations (Hakanson and Bryhn, 2008).

I recommend using satellite data, especially SeaWiFS and MODIS (Terra and Aqua) data that are freely available for the academic and research communities, in monitoring Kuwait coastal environments. The near-real-time availability of SeaWiFS and MODIS data and their synoptic spatial and temporal coverage make them a very advantageous tool for the coastal monitoring programs. Thus, integrating SeaWiFS and MODIS remotely sensed data with *in situ* measurements can add a valuable advancement for the current coastal environmental program of Kuwait.

Spatial and temporal distributions of Kuwait water clarity

The general spatial arrangement of Kuwait water clarity was mainly attributed to three factors: the Shatt Al-Arab discharge, northwestern counterclockwise water circulation of the Arabian Gulf, and coastal currents. The Shatt Al-Arab River plume directly affects Kuwait waters clarity, especially the northern waters and Kuwait Bay (Al-Ghadban and El-Sammak, 2005; Al-Yamani, 2008). The Shatt Al-Arab turbid waters discharging into the Arabian Gulf are deflected by the northwestern counterclockwise water circulation to the western bank of the Arabian Gulf, in Kuwait's territorial waters (Al-Yamani *et al*., 2004; Beg and Al-Ghadban, 2003; Heil et al. 2001) that contributes to the general increase in Kuwait water clarity from north to south. The northwestern counterclockwise water circulation was clearly illustrated by the Kuwait SST images that served as an important complementary data source for detecting water movements (Figure 9).

The increase of Kuwait water clarity from near-shore to offshore was attributed to coastal currents, water depth, wind-wave activity, and coastal morphology. The water currents in the shallow water areas increase, and consequently, enhance the vertical and horizontal mixing of water (Segar, 1998). Thus, the suspended particulate matter coming from the Shatt Al-Arab discharge are well mixed in shallow coasts, such as Kuwait Bay, compared to offshore waters. The increased vertical and horizontal mixing of waters in the shallow coasts also plays an important role in resuspending sediments that decrease the water clarity (Hakanson and Bryhn, 2008).

The wind-wave activity and coastal morphology are other important factors explaining the spatial distribution of Kuwait water clarity. The wind-wave activity creates the longshore coastal currents (Hakanson and Bryhn, 2008; Segar, 1998; Sverdrup *et al*., 2006) that move southward in agreement with the general water circulation of Kuwait's territorial waters (Al-Yamani *et al*., 2004). As the longshore coastal currents move southward, they transport the suspended particulate matter to the south coast: the longshore coastal currents continue moving southward until they are deflected toward offshore waters by the two headlands in the south (Ras Al-Julaiah and Ras Al-Zour) (Figure 4).

The temporal variations in Kuwait water clarity are influenced by the Shatt Al-Arab discharge variation. Unfortunately, information about the Shatt Al-Arab during the last three decades is virtually unavailable to the scientific community due to the continuous political conflicts in this region (Al-Hilli *et al*., 2009; Al-Yamani, 2008; Al-Yamani *et al*., 2004). Recent studies in the northern Kuwait waters, and the Karun, Tigris, and Euphrates Rivers, however, reveal that the maximum discharge of the Shatt Al-Arab might occur in February due to the water regulatory procedures in the upstream river and winter rainfall over the Shatt Al-Arab and adjacent areas. The Shatt Al-Arab discharge might also be increased in May as the remaining spring flood reaches downstream (Al-Yamani and Khvorov, 2007; Kangi and Heidari, 2008; Lapshin, 2000; Rahi and Halihan, 2009). The increase in the Shatt Al-Arab flow in winter greatly influenced Kuwait water clarity, while the flow increase in spring seemed to have negligible effect on Kuwait water clarity, especially on the southern waters of Kuwait. Perhaps, the southeastern wind that occurs most frequently in the spring, and the expected decrease in the Shatt Al-Arab flow during the spring due to the water regulatory procedures in the upstream river were the most significant factors that minimized the influence of the Shatt Al-Arab flow on Kuwait water clarity.

Conclusion

$K_d(490)$ and $K_d(488)$ showed a significant relationship with *in situ* SDD data (r^2= 0.67 and r^2= 0.68, respectively). The *in situ* SDD range used to establish the two Kuwait SDD models, derived from $K_d(490)$ and $K_d(488)$, represented the most of the water clarity variation within Kuwait's territorial waters. The Kuwait SDD models can be useful for various marine applications including fishery and marine ecology studies and coastal monitoring programs.

Kuwait water clarity increased from north to south and from near-shore to offshore. This spatial pattern of Kuwait water clarity was mainly attributed to three factors: the Shatt Al-Arab discharge, northwestern counterclockwise water circulation of the Arabian Gulf, and coastal currents. The Kuwait SDD increased from January to May and, then, started to decrease until November with a minor decrease in April and a minor increase in December. The temporal variations were greatly governed by the Shatt Al-Arab discharge variation. The water clarity in Kuwait Bay was very low compared to other Kuwait waters. The south coast waters had higher SDD values comparing to those in Kuwait Bay. The SDD temporal variation of the south coast followed the general temporal variation of Kuwait SDD, except that on the south coast SDD continued increasing until June. Kuwait water clarity temporally covaried with chlorophyll concentrations in certain months, while a temporal association between Kuwait water clarity and Kuwait SST was not observed.

The SeaWiFS and MODIS data compared to *in situ* measurements provided a comprehensive view of Kuwait SDD that improved the estimation of overall SSD mean within Kuwait waters. Also, the near-real-time availability of SeaWiFS and MODIS data and their highly temporal resolution make them a very advantageous tool for studying coastal environments. Thus, I recommend involving this method in monitoring Kuwait coastal environments.

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Table 1. Statistical comparison between the SeaWiFS SDD model and MODIS SDD model.

Parameters	SeaWiFS	MODIS
Study Period	11/1998-10/2004	1/2003-6/2007
N	80	66
r^2	0.67	0.68
In Situ Data Range	0.5 m -7.60 m	0.55 m -10.50 m
Mean $\widehat{SDD}$/*in situ* SDD*	1.06	1.07
Median $\widehat{SDD}$/*in situ* SDD	1.03	0.96
Mean PD	28.07%	30.02%
Median PD	22.98%	20.98%
Regression RMSE	0.75 m	1.08 m
Cross Validation RMSE	0.77 m	1.10

* $\widehat{SDD}$ is predicted SDD derived from the SDD models.

Table 2. Overall monthly mean SDD of Kuwait Bay, South Coast, and Kuwait waters.

	Overall monthly mean SDD (m)		
Months	Kuwait Bay	South Coast	Kuwait waters
January	1.15	3.11	2.71
February	1.22	3.33	2.87
March	1.10	4.15	3.62
April	1.01	4.00	3.55
May	1.33	4.98	4.44
June	1.14	5.12	4.37
July	1.16	4.74	4.15
August	1.15	3.83	3.26
September	1.17	3.44	3.00
October	1.12	3.18	2.74
November	1.05	3.08	2.65
December	1.16	3.26	2.85

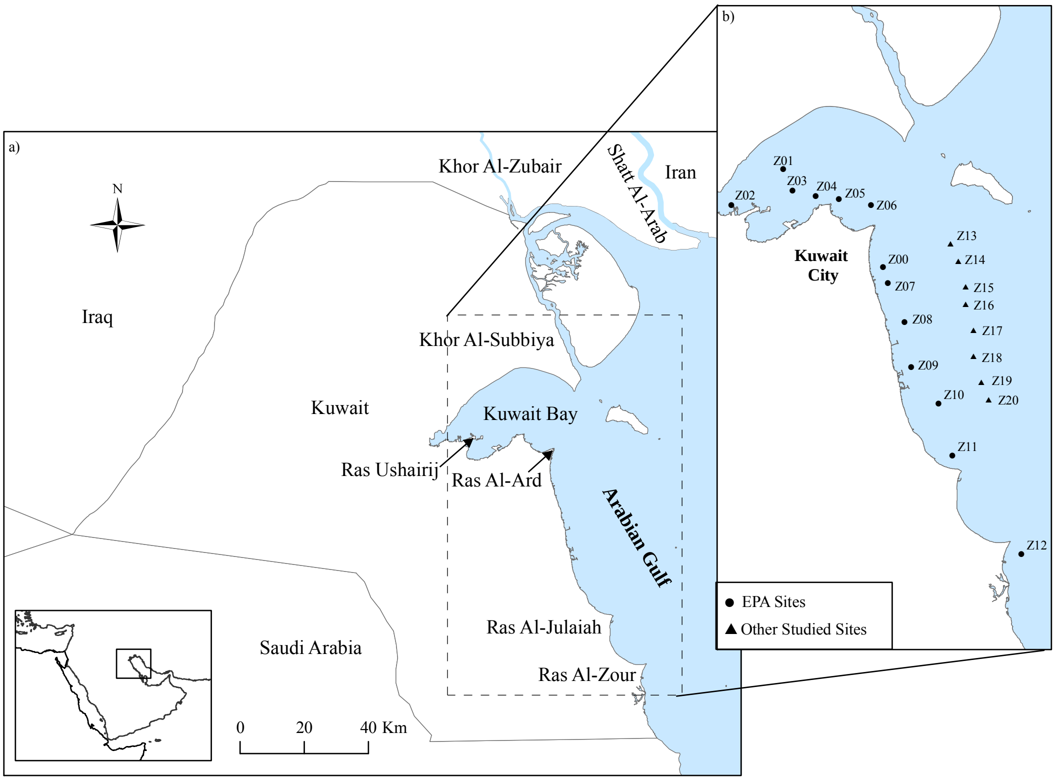

Figure 1. a) The study area and major headlands in the south Kuwait Bay and south coast. Note that the Shatt Al-Arab River and Khor Al-Zubair empty in the north of Kuwait's territorial waters. b) The study sites from where the *in situ* measurements were collected: study sites with circles are the EPA sites; and study sites with triangle illustrate the locations of my fieldwork during the summer of 2007. Note that the station Z02 was excluded from the analysis because of its adjacency to the shore.

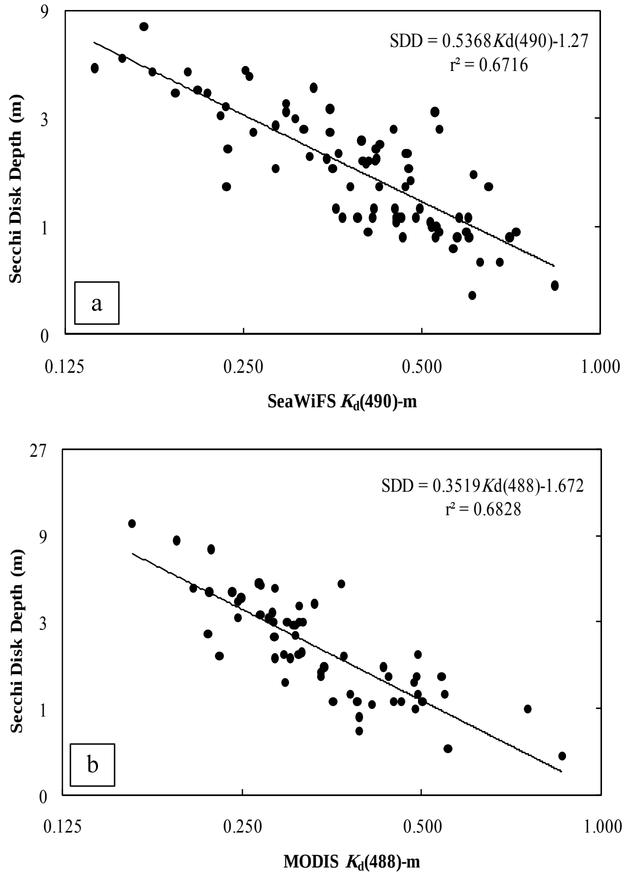

Figure 2. *In situ* SDD measurements exhibited a significant relationship with the semi-analytically derived K_d(490) of SeaWiFS (r^2 = 0.67, 0.5< SDD<7.6 m, n= 80). b) *In situ* SDD measurements exhibited a significant relationship with the semi-analytical K_d(488) MODIS (r^2 = 0.68, 0.55< SDD<10.50 m, *n*= 66).

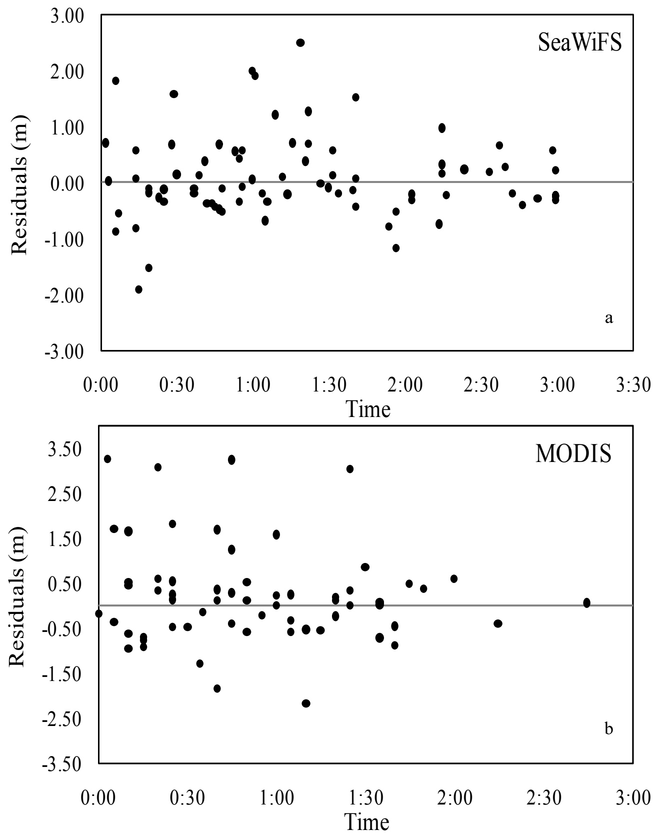

Figure 3. a) Regression residuals of the Kuwait SDD model derived from SeaWiFS K_d(490). The distribution of residuals indicates that the errors do not vary with the time. Note that *in situ* measurements matched with SeaWiFS K_d(490) images within 3 hours of satellite overpass had lower error compared to the other observations that might be attributed to the frequency occurrence of the data over the selected time. b) Regression residuals of the Kuwait SDD model derived from MODIS K_d(488). The distribution of residuals indicates that the errors do not vary with the time. Note that *in situ* measurements matched with SeaWiFS K_d(490) images within 2-3 hours of satellite overpass had lower error comparing to the other observations that, again, might be attributed to the frequency occurrence of the data over the selected time.

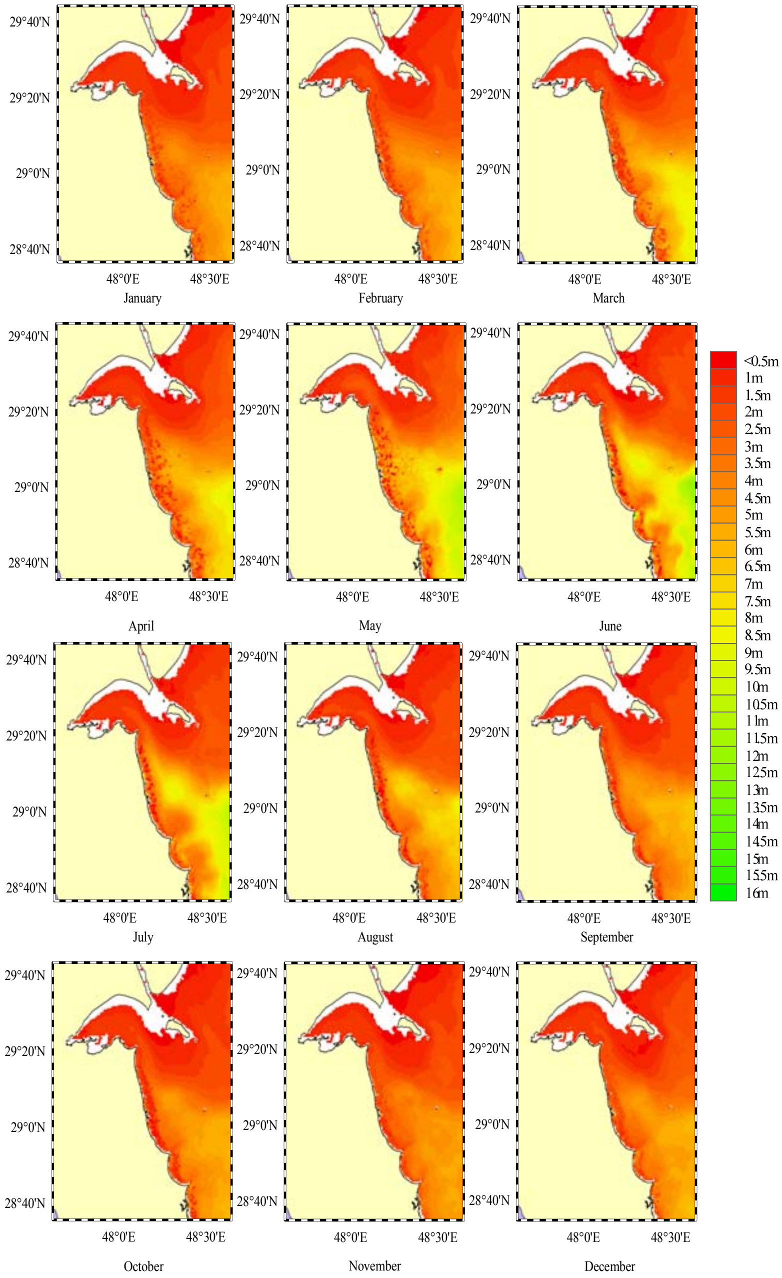

Figure 4. Shows the overall monthly mean SDD of Kuwait waters (November 1998-June 2007) derived from the modeled SeaWiFS and MODIS data. Kuwait water clarity increased from north to south and from near-shore to offshore. May-July exhibited the highest water clarity. Coastal morphology affects the SDD spatial distribution, especially the two headlands along the south coast, namely Ras Al-Julaiah and Ras Al-Zour.

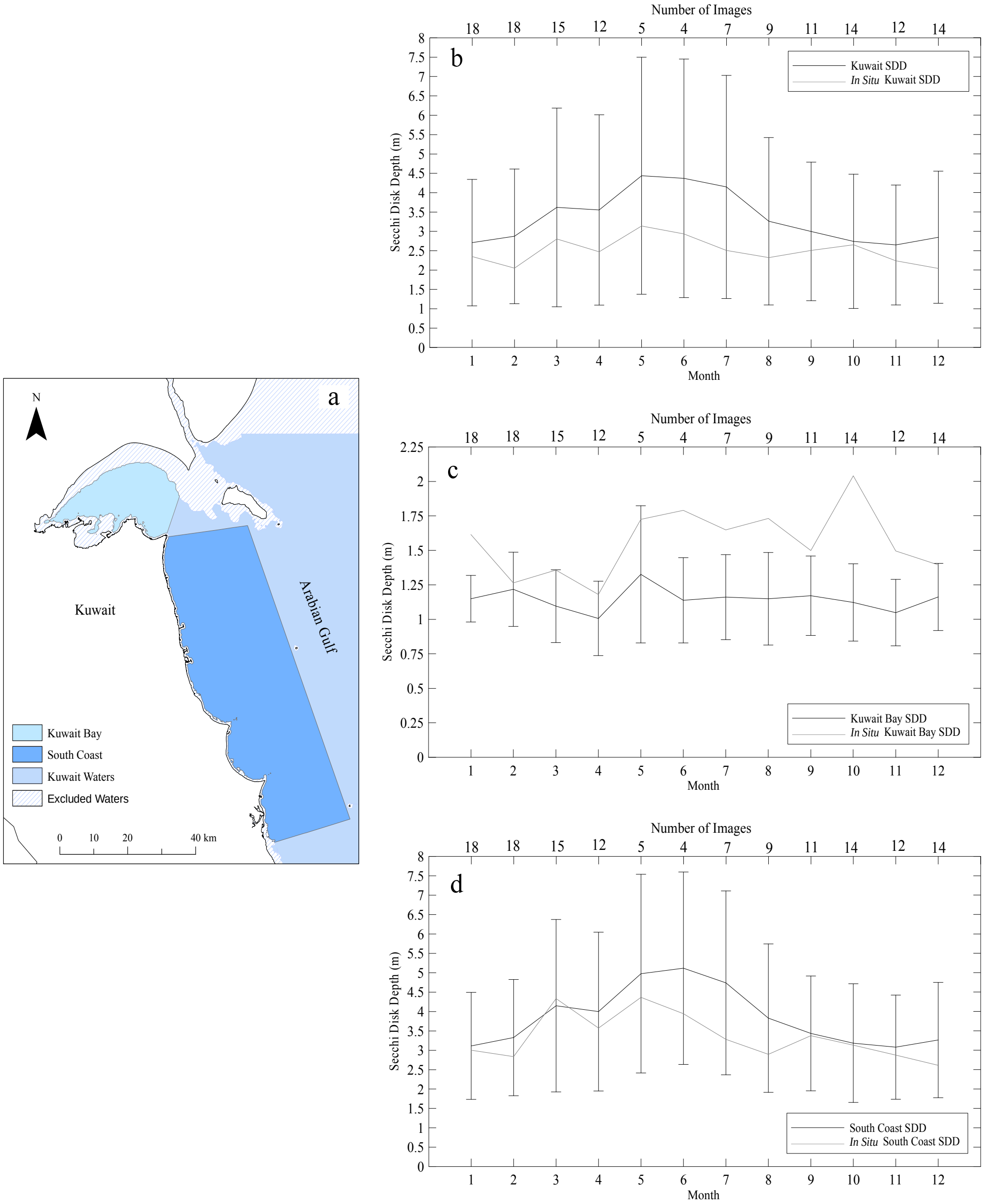

Figure 5. a) Geographic limits used to specify the overall monthly mean SDD of Kuwait Bay, South Coast, and the studied portion of Kuwait's territorial waters. The striped area represents shallow waters excluded from the analysis. b) Shows the overall temporal distribution of SDD within Kuwait waters. The highest overall mean SDD was in May. c) Overall temporal distribution of SDD within Kuwait Bay. The highest overall mean SDD was in May, but the temporal variation of SDD within Kuwait Bay was different from that within Kuwait waters. d) Overall temporal distribution of SDD within the South Coast. The highest overall mean SDD was in June.

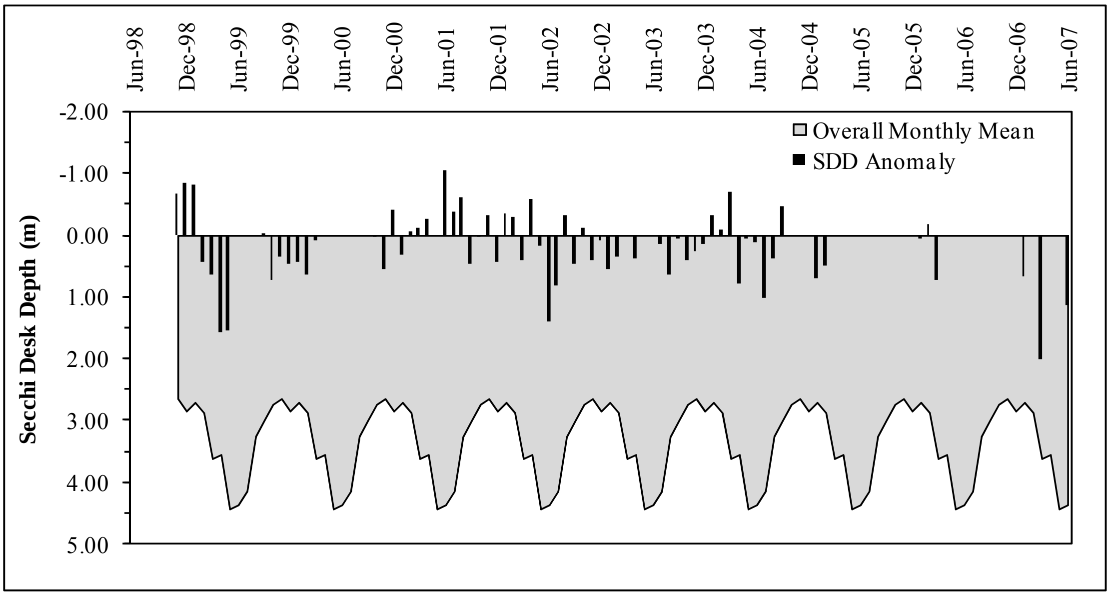

Figure 6. Difference between the monthly mean SDD of Kuwait waters (November 1998-June 2007) and the overall monthly mean SDD. Most monthly means have a bias from the overall monthly mean < ±1 m.

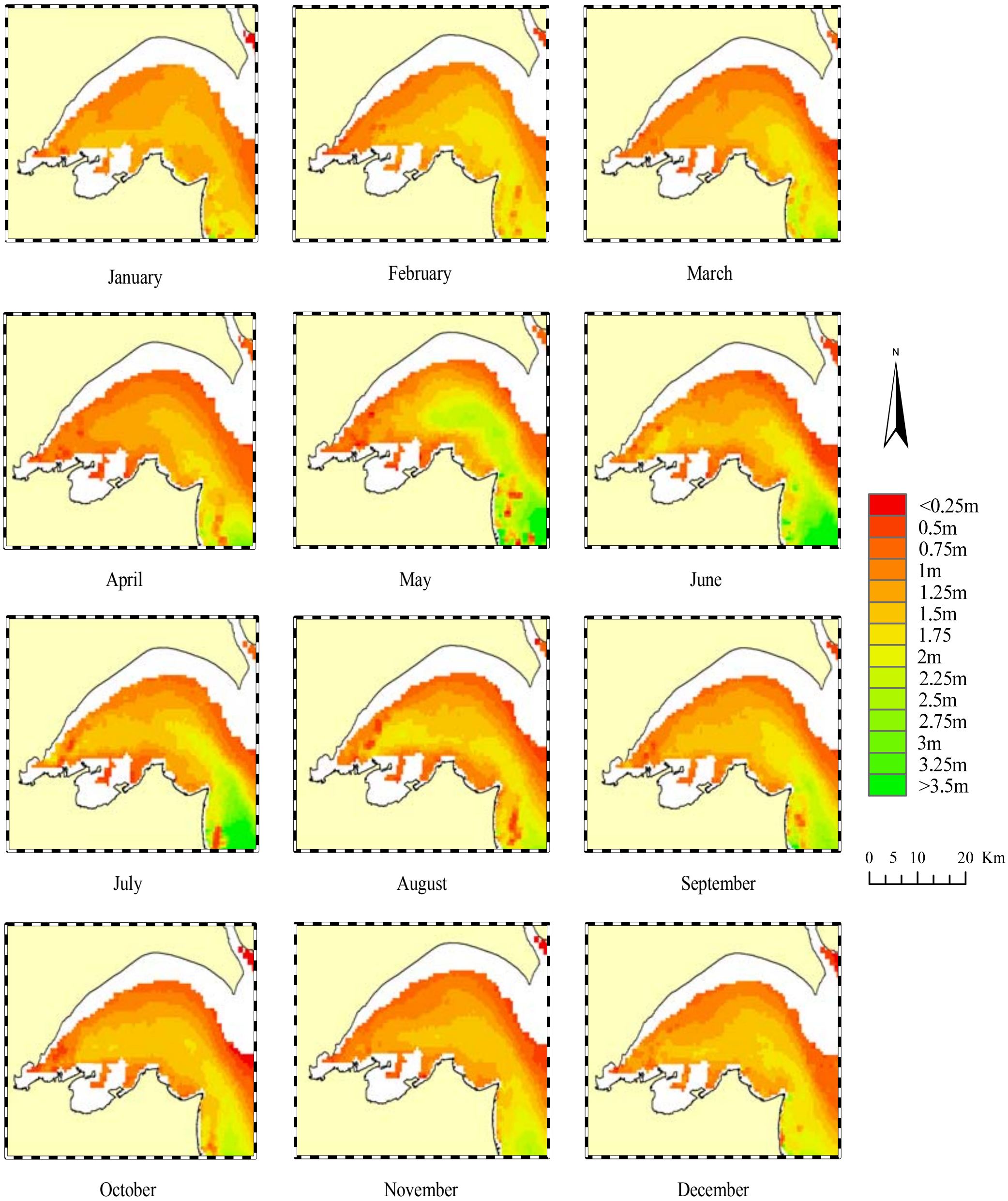

Figure 7. Overall monthly mean SSD in Kuwait Bay. The center of Kuwait Bay and its south entrance exhibited the highest SDD values around the year.

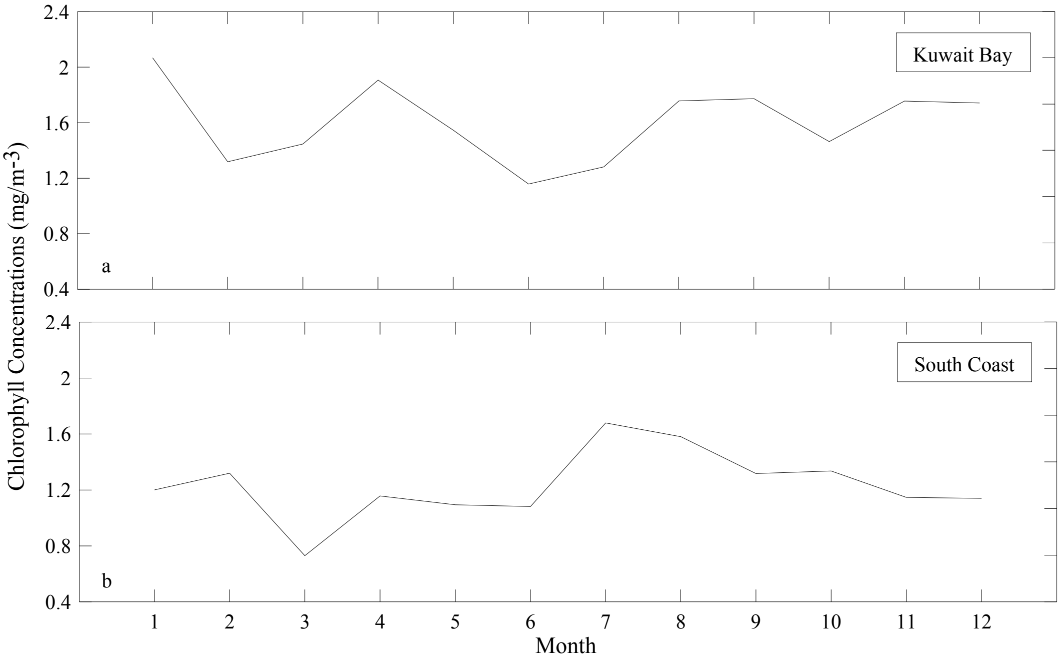

Figure 8. a) Overall monthly mean *in situ* chlorophyll concentrations (November 1998 –December 2006) observed in Kuwait Bay sites (Figure1b). b) Overall monthly mean *in situ* chlorophyll concentrations (November 1998 –December 2006) observed in the south coast sites (Figure 1b).

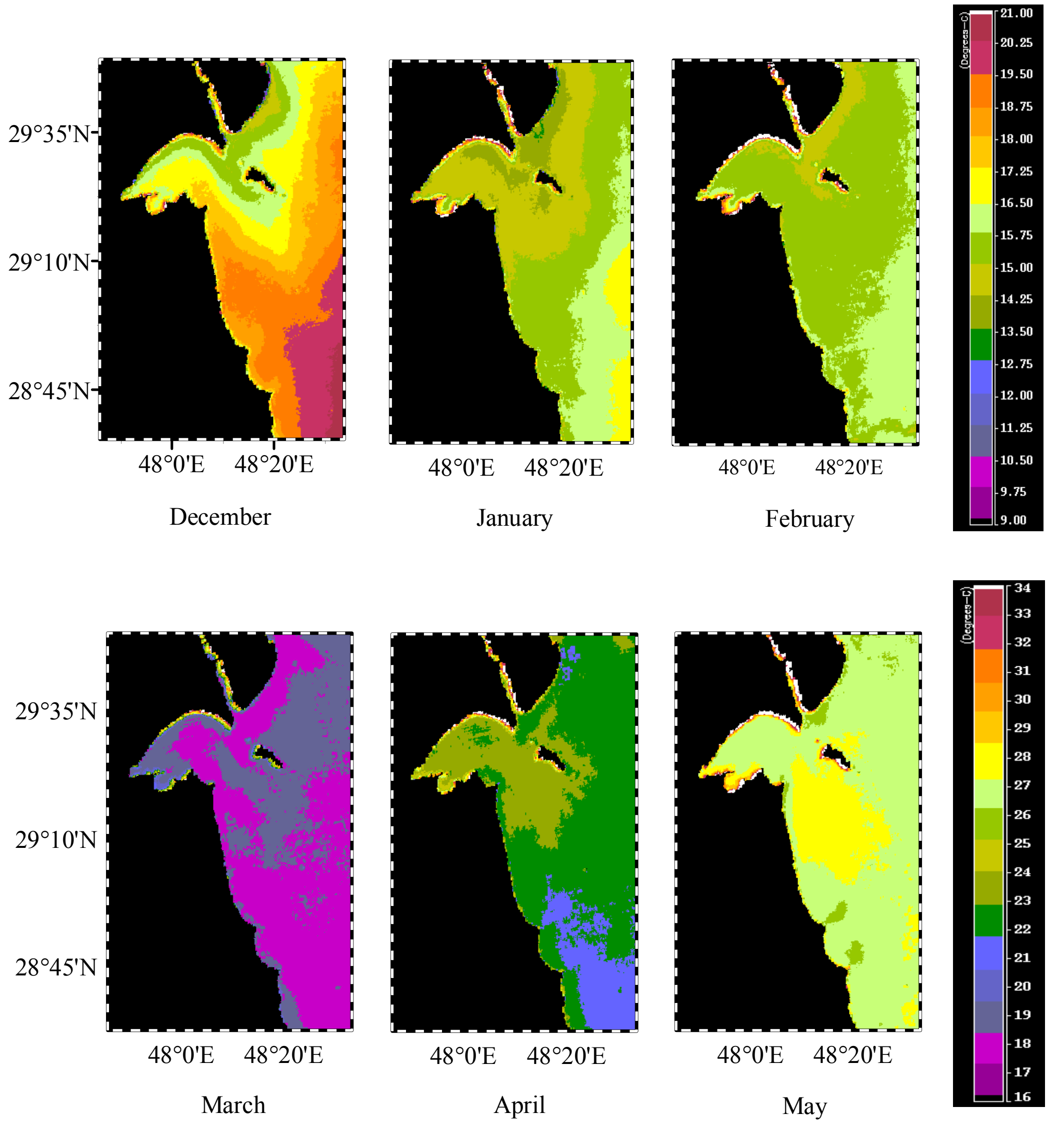

Figure 9. Overall monthly mean Kuwait SST derived from MODIS SST data discuss in Chapter 2. Note that both SDD (Figure 5) and SST of Kuwait waters are affected by coastal morphology and water depths that contributed to their distinct spatial patterns in Kuwait Bay and the south coast near the two headlands compared to the other areas.

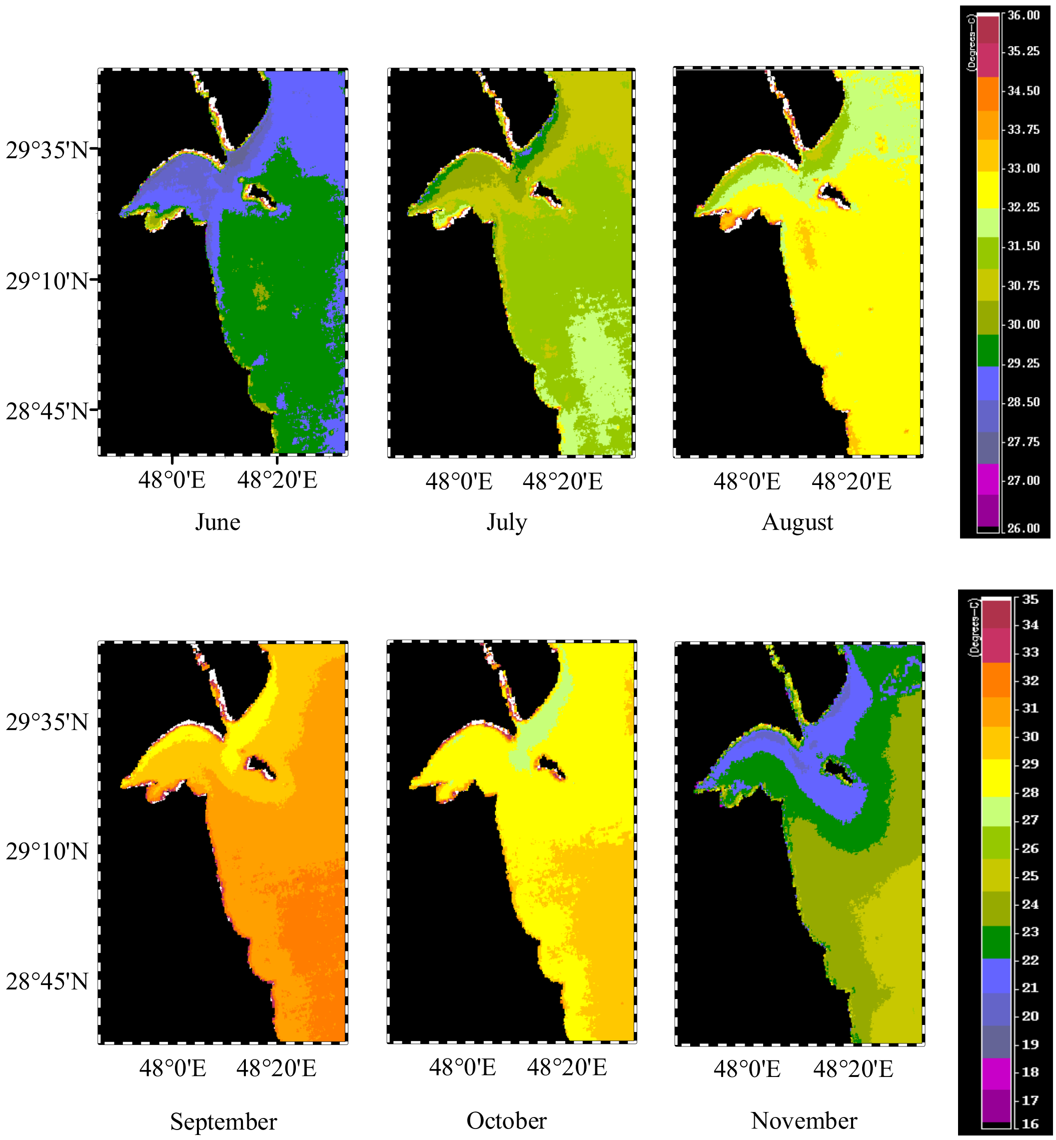

Figure 9 (continued).

Chapter 4

Summary and Conclusions

Summary

The coastal environment of Kuwait, located in the northwestern part of the Arabian (Persian) Gulf, is the main source of food, freshwater (by desalination) and electrical power for the State of Kuwait. Kuwait seawaters are rich in a diversity of fishery species, such as shrimps, *orange-spotted grouper* (Hamoor), and *silver pomfret* (Zobaidy) that provides about 40 to 50% of the country's seafood demand (Al-Yamani *et al*., 2004). Kuwait relies on desalination stations and power plants along the coast for its freshwater supply and electrical power. During the last three decades, the marine environment of Kuwait has been impacted by consequences of three major wars, destruction of Iraqi marshes, reduction of the Shatt Al-Arab discharge, and increased anthropogenic activities.

The Gulf War II (the most environmentally devastating war) in 1991 altered the chemical and physical characteristics of Kuwait's marine ecosystems. During that war, the Iraqi army pumped about eight million barrels of Kuwait oil into the Arabian Gulf and set all the oil wells on fire, which caused an environmental disaster not only in Kuwait, but also throughout the region (e.g., Al-Ghadban and El-Sammak, 2005; El-Baz and Al-Sarawi, 2000). The large quantity of oil pumped into the Gulf was a major threat to the desalination stations along the Arabian Gulf: two million barrels of oil were recovered at two locations about 400 km away from Kuwait City near Jubail and Duhran in Saudi Arabia (El-Baz and Al-Sarawi, 2000). Environmental consequences of these oil spills were left throughout the region for many years (Heil *et al*., 2001; Hussain and Gondal, 2007; Mostafawi, 2001).

The marine environment of Kuwait also encountered critical environmental changes when the Iraqi government started draining the Mesopotamian marshlands (locally named Al-Ahwar) in the early1990s through an artificial canal called the Third River that diverts Euphrates waters before reaching the marshes through another artificial canal called Shatt Al-Basra to the Khor Al-Zubair (Al-Hilli *et al*., 2009; Al-Yamani *et al*., 2004). The marshlands had covered an area of over 15,000 km^2. Most of these marshlands extend into southern Iraq at the confluence of the Euphrates and Tigris Rivers (Al-Hilli *et al*., 2009). Prior to their destruction, these marshlands served as critical habit for many plants, wildlife, and the domesticated animals of about 400,000 Ma'dans (Marsh Arabs) whose ancestors are believed to date back 5,000 years to the Sumerian civilization that developed the first alphabet and gave rise to the Babylonians (Ali, 2003). In 1995, satellite images showed that 90% of the Mesopotamian marshlands were dried (Al-Hilli *et al*., 2009).

These marshlands are considered among the most important marshlands in the world. They served as natural sediment and chemical pollutant filters to the effluents of the Euphrates River, but after their destruction, sediments, chemicals and wastewater flowed unimpeded from the Euphrates River through the drainage canals into the Khor Al-Zubair that empties into the Arabian Gulf near the Khor Al-Subbiya (Al-Ghadban and El-Sammak, 2005; Al-Yamani *et al*., 2004). The sea currents move these waters through the Khor Al-Subbiya into Kuwait Bay where over the past two decades they have had multiple impacts on aquatic plants and animals, especially in the northern marine environments of Kuwait (Beg and Al-Ghadban, 2003).

Moreover, the reduction of Shatt Al-Arab discharge due to upstream massive dam constructions has threatened the environmental balance of Kuwait marine ecosystems. The Shatt Al-Arab discharge, the main freshwater input in the north Arabian Gulf, used to play a valuable role in decreasing the salinity and supporting Kuwait seawaters with nutrients that made these environments optimum habitats for many marine organisms (Al-Yamani, 2008; Al-Yamani *et al.*, 2004). The Shatt Al-Arab is formed by three rivers: the Euphrates, Tigris, and Karun. These rivers during the past few decades have experienced increasing dam constructions that has reduced and changed the quality of the freshwater flow through these rivers (Al-Hilli *et al.*, 2009; Ertunc and Cetin, 2007; Foltz, 2002; Kangi and Heidari, 2008; Kibaroğlu, 2007; Kucukmehmetoglu, 2009; Lapshin, 2000).

The extensive regulation of the Euphrates, Tigris, and Karun Rivers is also expected to change the temporal variation of the Shatt Al-Arab discharge. Pre-1980 studies revealed that the Shatt Al-Arab inflow increased during December through June, with maximum discharge in May, because of heavy rainfall in the winter and melting of snow in Turkey, Syria, Iraq, and Iran in the spring (Al-Yamani *et al.*, 2004). Today, the spring flood is almost completely stored in reservoirs in the upstream countries where it used for drinking and irrigation during the dry months; while in winter, the river flow is released to generate hydro-electrical power (Kangi and Heidari, 2008; Lapshin, 2000; Rahi and Halihan, 2009) that causes the Euphrates to reach its maximum discharge in the winter rather than in the spring (Lapshin, 2000).

These new regulatory procedures are expected to increase the Shatt Al-Arab discharge in the winter months; and consequently, to cause the Kuwait seawater characteristics, such as salinity and nutrient concentrations, to fluctuate. The expected variation of the Shatt Al-Arab discharge agrees with the recent maximum salinity of northern Kuwait seawaters that occurs during February as reported by Al-Yamani *et al*. (2004) and Al-Yamani and Khvorov (2007).

The marine environments of Kuwait are also experiencing extensive disturbance due to development accompanied by increasing commercial, industrial, and recreational activities that are associated with human population growth. These activities place increased environmental stress on the marine ecosystem through the release of more sewage and increase in water temperatures that are elevated by nearby power plants (Bu-Olayan *et al*., 2001). The growing pressure on the coastal environment is suspected to be associated with documented massive fish die-offs that occurred in October, 1999 and September, 2001(Heil *et al*., 2001; Qasem, 2003; Rao *et al*., 2003). Heil *et al.* (2001) stated that the cause of the first fish die-off is unknown and might be related to one or a combination of factors, including the water currents that enhance transportation of pollutants from Iranian waters into Kuwait waters, increased organic nutrients, residual oil pollutants, undocumented pollutants discharged from the Khor Al-Zubair area, and increased urban waste including sewage and industrial waste.

Given the extreme importance of these coastal waters, and all the factors potentially negatively impacting the ecosystems of this area, a synoptic environmental monitoring program needs to be developed and implemented. Sea surface temperature (SST) and water clarity are important indicators of water quality and, thus highly influence the coastal ecosystem (Chen *et al*., 2007; Gentilhomme and Lizon, 1998). These water characteristics influence the productivity of marine organisms and explain their behaviors (Dippner, 1997; Van De Meutter *et al*., 2005). Traditional methods of collecting SST and water clarity data are logistically challenging and do not provide a high spatial-temporal synoptic perspective of these water characteristics. Thus, methodologies providing an accurate comprehensive perspective of the SST and water clarity of Kuwait marine environment, such as the integration of ground truth and remotely sensed data, are greatly needed (Al-Yamani *et al*., 2004; Nezlin *et al*., 2007).

Overall Project Goal

Previous oceanographic studies in the northwestern Arabian Gulf have been limited by the lack of establishing multitemporal analysis and using remote sensing technologies, especially the integration of *in situ* measurements with remotely sensed data (Al-Yamani *et al*., 2004; Nezlin *et al*., 2007). As a consequence, the spatial-temporal variability of important seawater characteristics, such as SST and water clarity, in this region remains unknown, or at least, their estimation remains scientifically insufficient. To my knowledge, empirical remotely sensed models measuring water clarity and SST within the northwestern Arabian Gulf waters have not been established. Based on limitations in estimating SST and water clarity described above, the goals of this study are to: 1) develop empirical models for measuring SST and water clarity of Kuwait seawaters; 2) map the spatial and temporal distributions of these water characteristics; and 3) assess the interrelationships between these two water characteristics, by addressing the following questions:

1. What is the relationship between remotely sensed spectral measurements and *in situ* measurements of SST and water clarity in the Kuwait ocean coastal region?
2. Does this relationship vary spatially and/or temporally?

If a relationship between remotely sensed spectral measurements and *in situ* SST and water clarity can be established, the following questions will also be addressed:

3. What factors influence SST and water clarity model accuracy?
4. How does the accuracy of these modeled seawater characteristics vary spatially and/or temporally?
5. What are the spatial and temporal distributions of these Kuwait seawater characteristics?
6. What are the interrelationships between SST and water clarity of Kuwait seawaters?

Chapter 2: Mapping Spatial and Temporal distributions of Kuwait SST Using MODIS Remotely Sensed Data

Chapter 2 Study Goal

Previous oceanographic studies in the northwestern Arabian Gulf have been limited by the lack of multitemporal analysis and use of remote sensing technologies, especially the integration of *in situ* measurements with remotely sensed data (Al-Yamani *et al*., 2004; Nezlin *et al*., 2007). As a consequence, the spatial-temporal variability of important seawater characteristics, such as SST, in this region remains unknown: or at least, their estimation remains scientifically insufficient. To my knowledge, empirical remotely sensed models measuring SST within the northwestern Arabian Gulf waters have not been established. The goals of this study were to: 1) develop an empirical model for measuring Kuwait SST using the SST ocean product of Moderate Resolution Imaging Spectroradiometer (MODIS) (Feldman and McClain, 2008); 2) map the spatial and temporal distributions of Kuwait SST for the period of January 2003 to July 2007.

Chapter 2 Conclusion

The SST MODIS showed a significant relationship with *in situ* SST data (r^2= 0.98, RMSE = 0.7 ^{o}C). The Kuwait SST model derived from SST MODIS data was efficient in mapping the Kuwait SST in all seasons. The Kuwait SST model can be used in many marine applications including coastal marine ecology applications, and marine biology applications. Also, the model can be used as a complementary means to study wind driven water circulations of the northwestern part of the Arabian Gulf

The overall monthly mean of Kuwait SST images illustrated distinct spatial and temporal distributions. Northern Kuwait's waters, including Kuwait Bay, had lower SSTs comparing with south waters, especially south offshore waters. This spatial arrangement was dominant in the winter, middle and later summer, and fall, whereas in spring, especially in March and April, this spatial arrangement was totally reversed. May and June seemed to be a transition period between the two patterns. Kuwait SST exhibited the highest spatial variability in November and December, while the lowest spatial variability of SST was observed in February and March. The temporal variation of Kuwait SST was greatly influenced by the seasonal variation of solar intensity and air temperatures. Kuwait SST increased from January to August, and then decreased to December.

In Kuwait Bay, the spatial distribution of SST was generally influenced by the spatial distribution of Kuwait SST. Kuwait Bay SST exhibited the highest spatial variability in November, while the lowest spatial variability of SST was observed in February, which agreed with those observed for the Kuwait waters. Kuwait Bay SST had the same temporal variation with Kuwait SST. Also, the spatial distribution of SST in the south coast was clearly influenced by the overall spatial distribution of Kuwait SST. South coast SST exhibited the highest spatial variability in December, while the lowest spatial variability of SST was observed in March, which again agreed with those observed for the Kuwait waters.

The spatial arrangement of Kuwait SST was mainly attributed to the northwestern counterclockwise water circulation of the Arabian Gulf, wind direction and intensity, wind-wave activity and coastal morphology. The temporal variability of these factors played an important role in understanding the spatial arrangement of Kuwait SST. The temporal distribution of Kuwait SST was highly associated with seasonal variations of air temperatures with one month of lag in Kuwait SST when comparing the highest SST to the highest air temperature. This association was due to the heat exchange between sea surface layers and the adjacent atmospheric layers whose effect increases intensively in shallow waters.

The MODIS data compared to *in situ* measurements provided a comprehensive view of the Kuwait SST that improved the estimation of overall SST mean within Kuwait's waters. Also, the near-real-time availability of SeaWiFS and MODIS data and their highly temporal resolution make them a very advantageous tool for studying coastal environments. Thus, I recommend involving this method in monitoring Kuwait coastal environments.

Chapter 3: Modeling Kuwait Seawater Clarity: A Spatial-Temporal Study Using Remote Sensing and GIS

Chapter 3 Study Goal

Previous oceanographic studies in the northwestern Arabian Gulf have been limited by the lack of multitemporal analysis and use of remote sensing technologies, especially the integration of *in situ* measurements with remotely sensed data (Al-Yamani *et al*., 2004; Nezlin *et al*., 2007). As a consequence, the spatial-temporal variability of important seawater characteristics, such as water clarity, in this region remains unknown, or at least, their estimation remains scientifically insufficient. To my knowledge, empirical remotely sensed models measuring water clarity within the northwestern Arabian Gulf waters have not been established. The goals of this study were to: 1) develop two empirical models for estimating Kuwait water clarity using the semi-analytical derived $K_d(490)$ and $K_d(488)$ of Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and MODIS, respectively (Feldman and McClain, 2008a, b) ; 2) map the spatial and temporal distributions of Kuwait water clarity for the period of November 1998 to June 2007; and 3) assess the interrelationships between water clarity and SST, and chlorophyll concentrations within Kuwait seawaters.

Chapter 3 Conclusion

$K_d(490)$ and $K_d(488)$ showed a significant relationship with *in situ* Secchi Disk Depth (SDD) data (r^2= 0.67 and r^2= 0.68, respectively). The *in situ* SDD range used to establish the two Kuwait SDD models, derived from $K_d(490)$ and $K_d(488)$, represented the most of the water clarity variation within Kuwait's territorial waters. The Kuwait SDD models can be useful for various marine applications including fishery and marine ecology studies and coastal monitoring programs.

Kuwait water clarity increased from north to south and from near-shore to offshore. This spatial pattern of Kuwait water clarity was mainly attributed to three factors: the Shatt Al-Arab discharge, northwestern counterclockwise water circulation of the Arabian Gulf, and coastal currents. The Kuwait SDD increased from January to May and, then, started to decrease until November with a minor decrease in April and a minor increase in December. The temporal variations were greatly governed by the Shatt Al-Arab discharge variation. The water clarity in Kuwait Bay was very low compared to other Kuwait waters. The south coast waters had higher SDD values comparing to those in Kuwait Bay. The SDD temporal variation of the south coast followed the general temporal variation of Kuwait SDD, except that on the south coast SDD continued increasing until June. Kuwait water clarity temporally covaried with chlorophyll concentrations in certain months, while a temporal association between Kuwait water clarity and Kuwait SST was not observed.

The SeaWiFS and MODIS data compared to *in situ* measurements provided a comprehensive view of Kuwait SDD that improved the estimation of overall SSD mean within Kuwait waters. Also, the near-real-time availability of SeaWiFS and MODIS data and their highly temporal resolution make them a very advantageous tool for studying coastal environments. Thus, I recommend involving this method in monitoring Kuwait coastal environments.

Significance

The integration of remotely sensed data with *in situ* measurements is a great advancement in marine studies that helps accurately illustrating relationships among environmental variables in a comprehensive view. This study provided a methodology to integrate remotely sensed data (SeaWiFS and MODIS) with *in situ* measurements for studying two important water characteristics, SST and water clarity, within Kuwait's waters. I have shown that the remotely sensed data can sufficiently estimate SST and water clarity within Kuwait's waters and, consequently, accurately illustrate the spatial and temporal variability of these water characteristics in a comprehensive perspective.

The sufficiently accurate comprehensive perspective of Kuwait SST and SDD, a water clarity measure, demonstrated the role of critical environmental factors, such as northwestern water circulation of the Arabian Gulf, wind direction and intensity, and Shatt Al-Arab discharge, on these water characteristics. Illustrating the role of these environmental variables on Kuwait SST and water clarity should contribute in improving the general model of Kuwait's coastal environment. Also, the comprehensive view of Kuwait SST and water clarity should facilitate the future coastal applications including fisheries and coastal marine ecology applications. For instance, the role of SST, which can reflect the entire water column temperature due to the great vertical and horizontal mixing of Kuwait's coastal waters, on marine organisms as a fundamental habitat characteristic can be comprehensively investigated using the Kuwait SST model. Also, the role of water clarity on the prey-predator interactions or forage areas can be comprehensively studied using the Kuwait SDD models.

The Kuwait SST and SDD models were derived from SeaWiFS and MODIS remotely sensed data. These two satellites have great features for marine applications. Their high temporal, spectral, and radiometric resolutions and near-real-time availability are significant features for marine applications, especially coastal monitoring programs. Thus, I recommend involving the Kuwait SST and SDD models in monitoring Kuwait coastal environments: integrating these two models data with *in situ* measurements can add a valuable advancement for the current coastal environmental program of Kuwait.

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Appendix

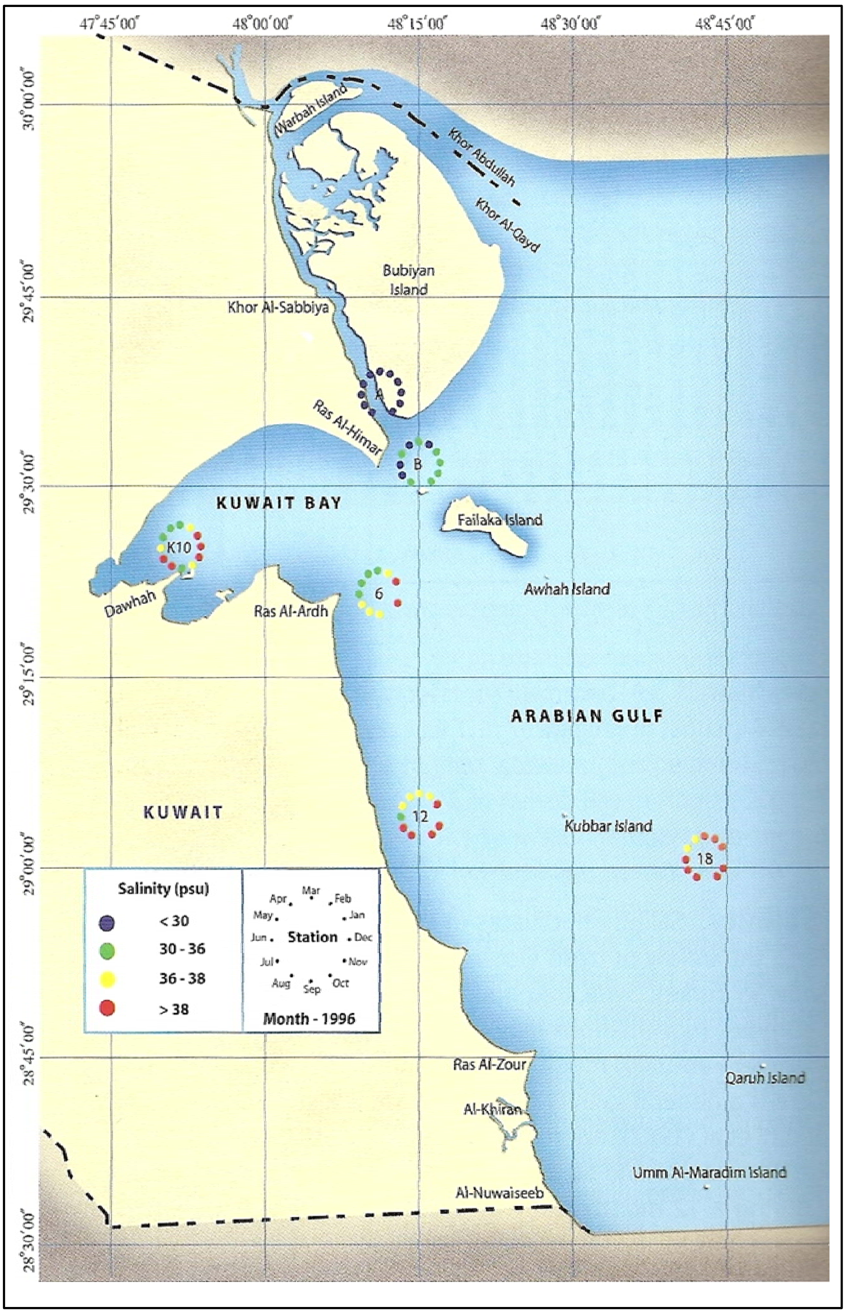

Figure A. The spatial and temporal variation of the salinity of Kuwait waters during 1996 (Al-Yamani *et al*, 2004).

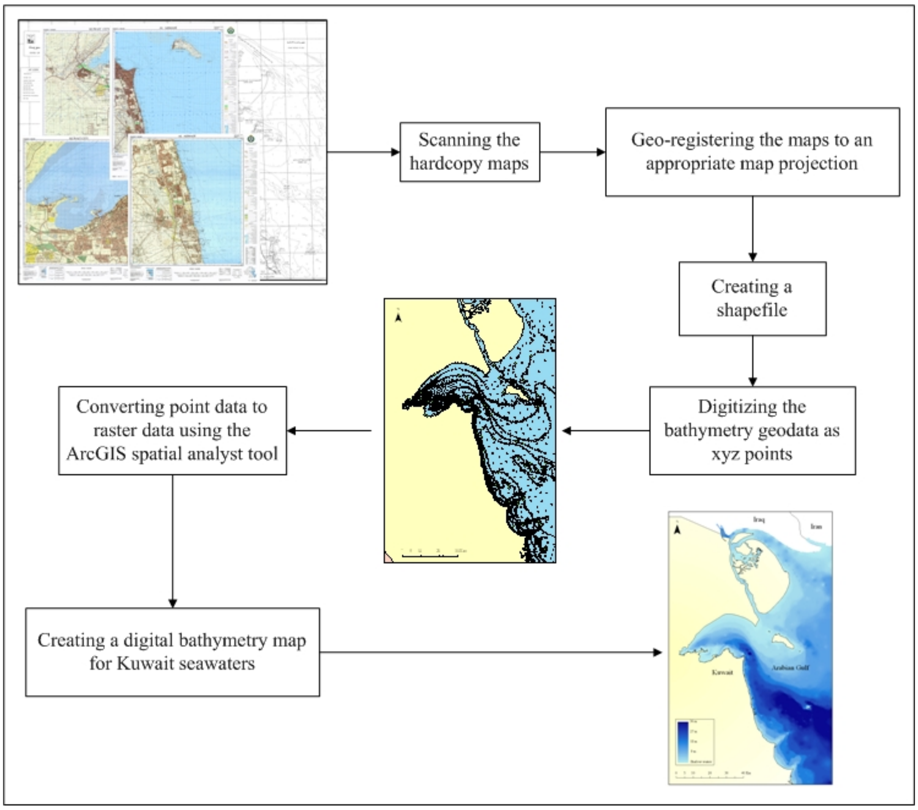

Figure B. Processes of creating the bathymetry map of Kuwait waters.

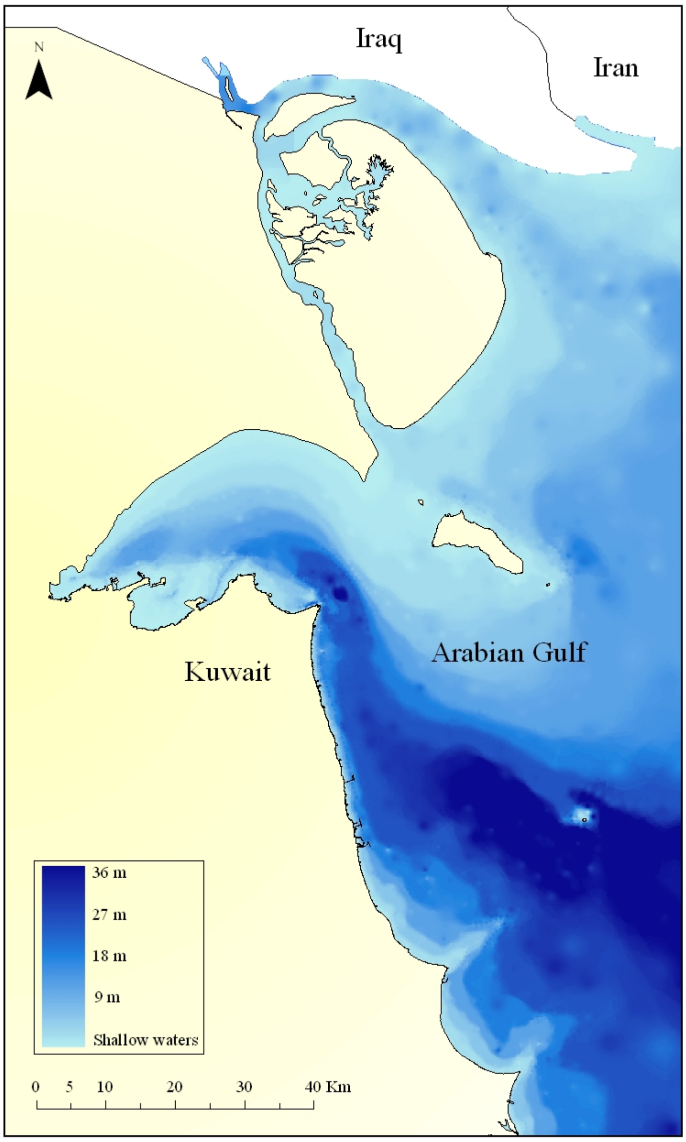

Figure C. Bathymetry map of Kuwait seawaters: the north area including Kuwait Bay is shallow, except the southeastern Kuwait Bay. The south waters are mostly deeper than 15 m. The bathymetry map were digitized based on nine detailed hardcopy bathymetry maps of Kuwait (at scale of 1:50,000) produced by the Defense Ministry of Kuwait (1995).

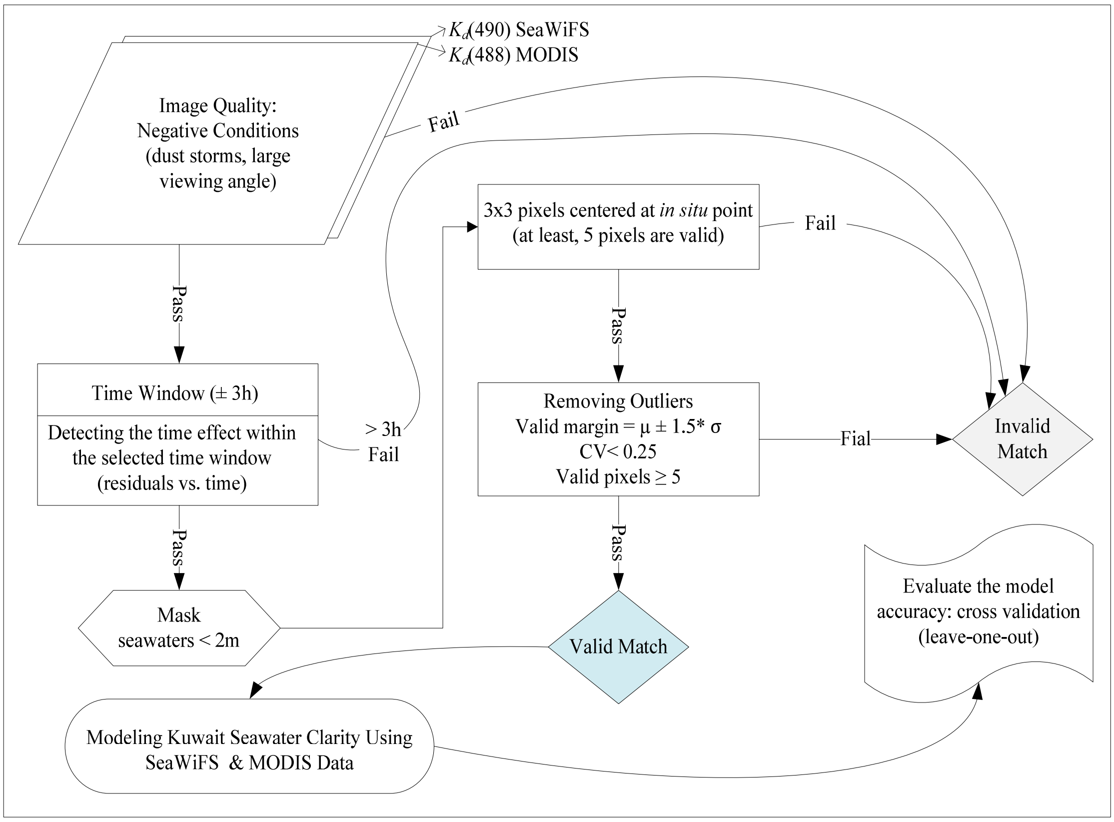

Figure D. The satellite image and *in situ* measurements matchup processes.

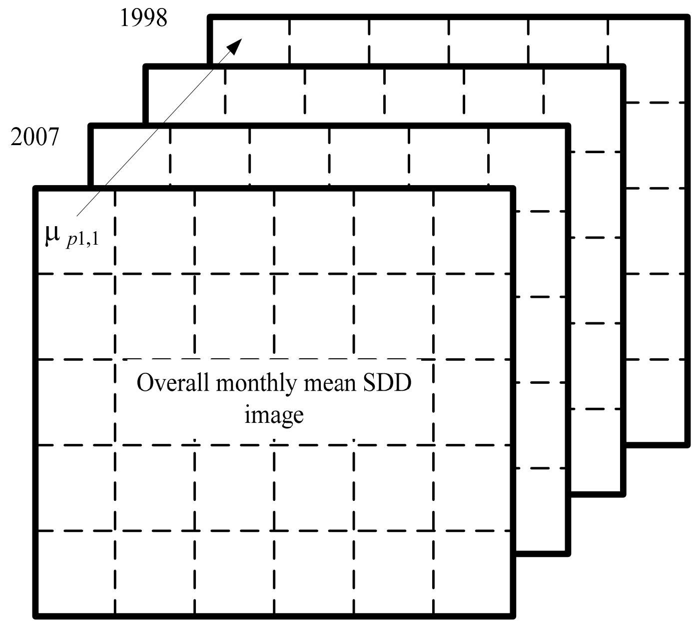

Figure E. An explanation of calculating the overall monthly mean SDD of each calendar month.

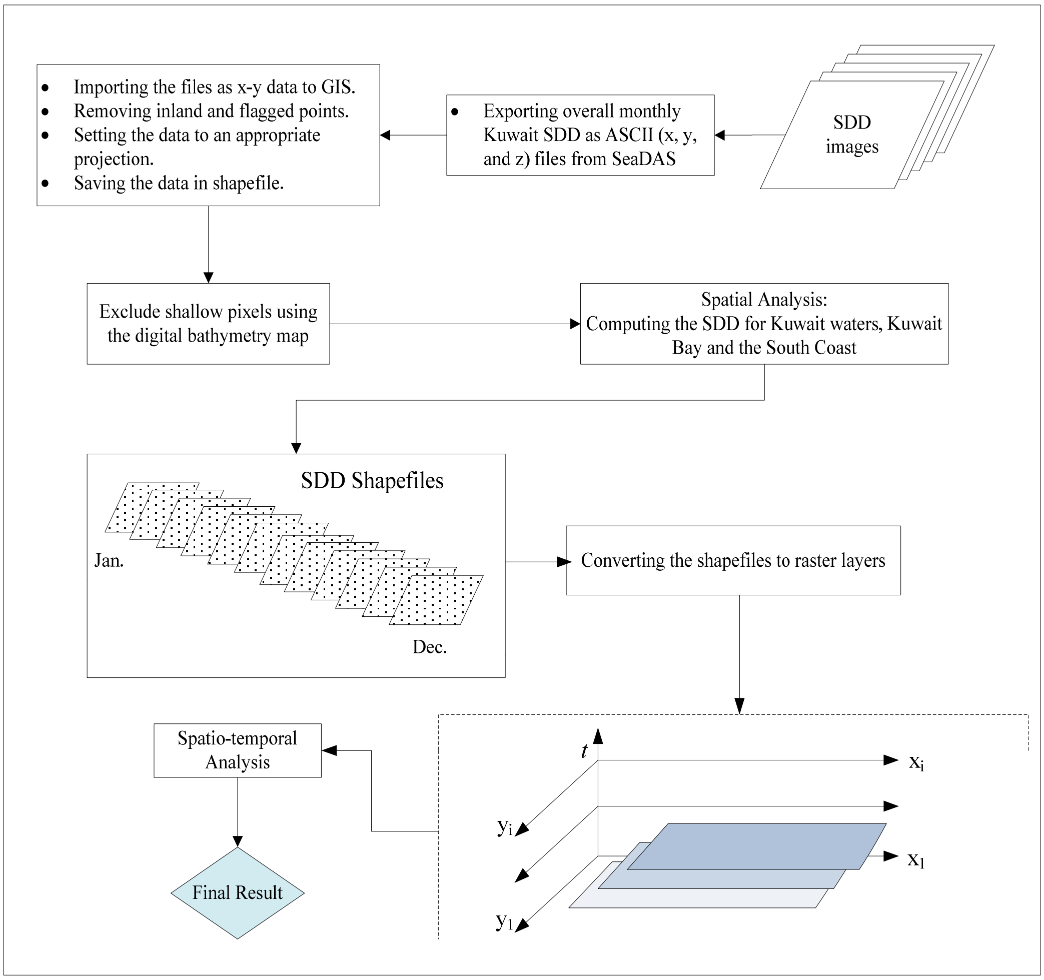

Figure F. SSD images imported into the GIS to analyze the spatial-temporal distribution of Kuwait water clarity.

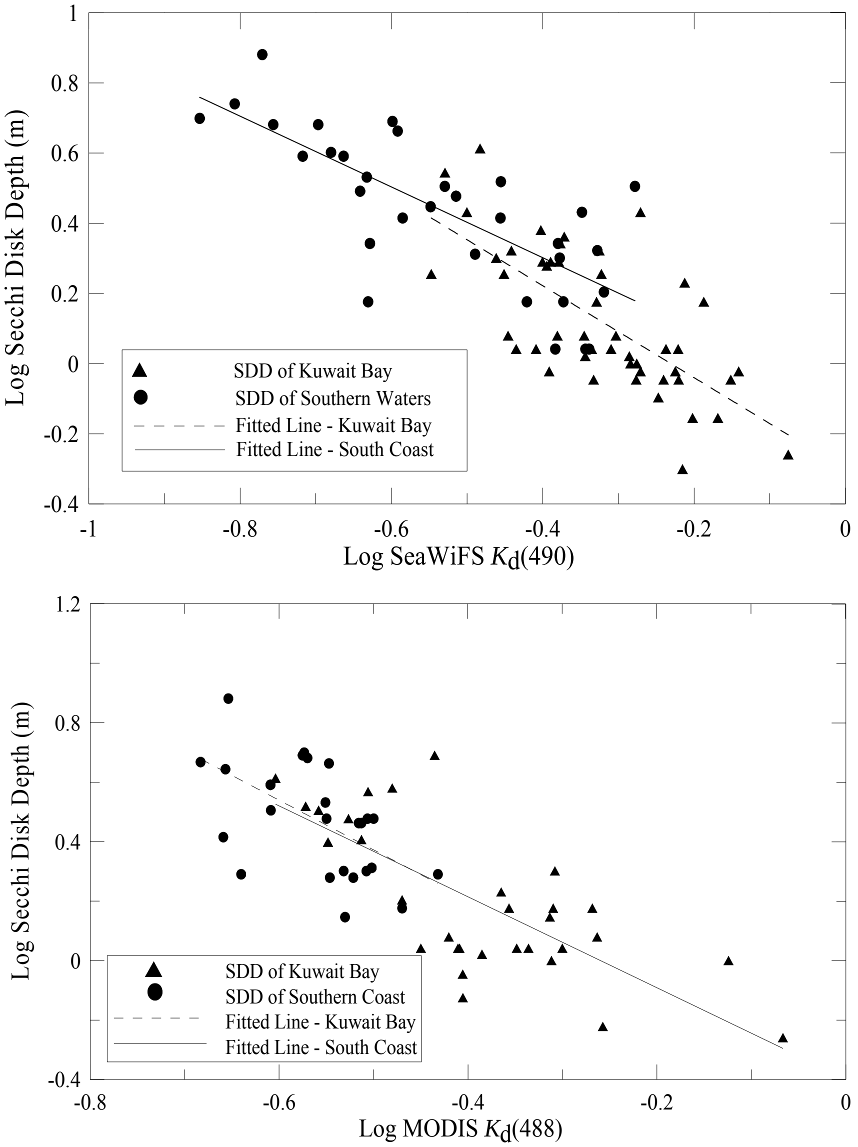

Figure G. a) Visual test, pre-dummy variable analysis, illustrating differences between the fitted line of Kuwait Bay data (*in situ* SSD versus SeaWiFS $K_d(490)$) and the fitted line of South Coast data (*in situ* SSD versus SeaWiFS $K_d(490)$). b) Differences between the fitted line of Kuwait Bay data (*in situ* SSD versus MODIS $K_d(488)$) and the fitted line of South Coast data (*in situ* SSD versus MODIS $K_d(488)$). Because the fitted lines of Kuwait Bay data and South Coast data in both graphs were visually different in their slope and y-intercept, the dummy variable analysis was used to detect whether the differences in the slope and y-intercept were significant.