

ENVIRONMENTAL STUDIES OF THE ARABIAN SEA USING REMOTE SENSING, GIS AND GPS TECHNIQUES

A DISSERTATION

*Submitted in partial fulfillment of the requirement for the award of the
degree*

Of

MASTER OF SCIENCE

In

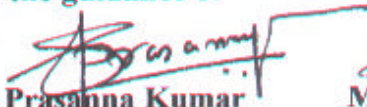
GEOINFORMATICS

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CERTIFICATE

This is to certify that Miss Ashlesha Saxena, student of Master of Geoinformatics (MSc. Geoinformatics) from Department of Applied Geology, Barkatullah University, Bhopal – 462026, India, has successfully undertaken and completed her project work title “ENVIRONMENTAL STUDIES OF THE ARABIAN SEA USING REMOTE SENSING, GIS AND GPS TECHNIQUES” under the guidance of Dr. S Prasanna Kumar and Mr. Andrew Menezes at National Institute of Oceanography (NIO), Goa. She has done this project work during 1 March to 30 June at NIO, Goa.

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CADIDATE'S DECLARATION

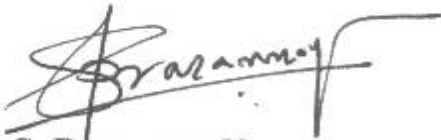
I hereby declare that, the work which is being presented in the dissertation work entitled "ENVIRONMENTAL STUDIES OF THE ARABIAN SEA USING REMOTE SENSING, GIS AND GPS TECHNIQUES" in partial fulfillment of requirement for the award of the degree of **MASTER OF SCIENCE in GEOINFORMATICS** and submitted in the Department of Applied Geology, Barkatullah University, Bhopal (M.P.), is an authentic record of my own work, conducted under the supervision of **Dr. D.C. Gupta**, Department of Applied Geology, Barkatullah University, Bhopal (M.P.), and co-supervision of **Dr. S. Prasanna Kumar**, Scientist, POD, NIO and **Mr. A. Menezes**, Scientist, MID, NIO at National Institute of Oceanography, Goa


I further declare that to best of my knowledge that the dissertation report does not contain any part of any work, which has been submitted for the award of any degree either in this university or in any other University without proper citation.


(ASHLESHA SAXENA)

This is to certify that, the above statement made by the candidate is corrected to the best of our knowledge.

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ACKNOWLEDEMENTS

It gives me immense pleasure to express my deep sense of gratitude to my guide, Dr. D.C Gupta, Professor and Head, Department of Applied Geology, Barkatullah University, Bhopal, for permitting me to carry out my project at National Institute of Oceanography, GOA. His constant encouragement, keen interest, worthy guidance, valuable suggestion and critical evaluation of the investigation result throughout the academic period has immensely help me for successful completion of my work.

I am highly indebted to **Dr. S. Prasanna Kumar Scientist, POD National Institute of Oceanography, GOA**, who gracefully accepted to be my guide and his continued inspiration and efficient guidance throughout the dissertation work. The present work is the result of his constant involvement in the investigation and readiness to explore scientific ideas as applicable to the present study.

I express my sincere thanks to **Mr. A. Menezes Scientist, MID National Institute of Oceanography, GOA**. For the enthusiasm and inspiration, which was always here whenever I need it.

I would take this opportunity to express my gratitude to the **National Institute of Oceanography, GOA**, for all the facilities provided. In this regard **Mr. P.V.Sathe (scientist), Mr.Gorish salgaonkar (Project Trainee) National Institute of Oceanography, GOA**, for his helping nature.

I express my sincere thanks to **Dr.K.K. Rao, and Mr. A.M. Singh**, Department of Applied Geology, Barkatullah University, Bhopal for their valuable suggestion whenever required during my M.Sc. (Geoinformatics) course.

I am thankful to **Mr. Rajiv K. Singh**, Lectures, and **Dr. Pradeep Shrivastava** staff, Department of Applied Geology, Barkatullah University, Bhopal for his cooperation suggestion.

With immense pleasure I would acknowledge the help and cooperation extend to me by my colleagues. First of all I would like to thanks **Mr. Chandrapal Gill** whose constant encouragement, suggestion and moral support. I would like to express my sincere thanks to **Miss Neelam Soni**, **Mr. Bharti Dasian** for their help and suggestion whenever required.

My heartfelt thanks to my friends **Miss Manju Nagrajan**, **Mr. Balkrishan Patidar** along with whom I was associated for four-moths of dissertation period for their constant encouragement and help in compilation of my project work.

I take this opportunity to thanks all other **staff at NIO** who gives me full support whenever it was in need directly and also indirectly at all times during my stay at Goa for my project work.

Above all these it is because of my *beloved parents* who had taken painstaking effort to bring me up of this level and solemnly place all the credits for this project work at their feet and also thankful to other family member who help me in all aspect in all time.

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CHAPTER I

INTRODUCTION

General Introduction

The Ocean covers 71% of the earth's surface compare to 29% of land area. The major oceans are the Southern Ocean, the Atlantic Ocean, the Pacific Ocean, the Indian Ocean and Aractic Ocean. The last four oceans are clearly divided from each other by landmasses, but the division between the southern ocean and the others to its north are determined only by the characters tics of the ocean water. The proportion of water to land in the southern hemisphere is much greater (4:1) than in the northern hemisphere (1:5). The Pacific Ocean occupied about 46% of the total world ocean area, the Atlantic Ocean about 23% the Indian Ocean about 20%, the rest combined about 11%. Thus, the Indian Ocean is the smallest of all the oceans and it is also the least explored one compared to the Atlantic and the Pacific. The northern Indian ocean is distinctly different from the rest of the wold ocean as it experiences seasonal reversal of winds called monsoons.

Geography of the Arabian Sea

The Arabian Sea situated in the western part of the northern Indian Ocean is a tropical basin. It is bounded on the east by Indian peninsula, on the north by Baluchistan and Sindh provinces of Pakistan and on the east by the landmass of Arabia and Africa. The width of the Arabian Sea basin is about 2,400 km and average depth is 4,652 meters. The basin covers an area of 73,556,000 square kilometers including the Red Sea and the Persian Gulf, while its volume is estimated to be 292,131,000 cubic kilometers.

Hydrographic characteristics

The Arabian Sea experiences seasonal reversal of winds, which changes semi-annually. During June to September strong, about 15m/s, winds from southwesterly direction blows over the Arabian Sea and into the Indian subcontinent bringing heavy rainfall. This period is known as summer or southwest monsoon season. During November to February, comparatively weaker winds, 5 m/s, from northeasterly direction blow over the Arabian Sea from the continent. This period is known as winter or northeast monsoon season. Between these two monsoons, winds are weak and variable. In response to this semi-annual atmospheric forcing, the hydrographic characteristics as well as the circulation of the Arabian Sea also undergo seasonal change. During summer monsoon, strong upwelling occurs along the coasts of Somalia, Arabia and along the southern part of the southwest coast of India. This upwelling, in turn, supports a large fishery in the Arabian Sea. In addition, Arabian Sea loses fresh water to the tune of ~1m annually through intense evaporation. Lack of fresh water runoff from any major rivers, the excessive evaporation over precipitation (E-P) as well as proximity to the Red Sea and Persian Gulf makes the surface salinity of Arabian Sea high, in excess of 36psu (practical salinity unit).

Motivation

Arabian Sea is one of the most productive regions of the world ocean. Biological productivity of a region is closely related to the fisheries of that region. India with its population over a billion people, most of which is located close to the coast, have to depend more and more up on the ocean for its food and nutrition needs. Hence it is very important to understand the distribution and variability of the chlorophyll (phytoplankton) and the factors responsible for it.

Study Domain

In order to understand the environmental factors responsible for the distribution and variability of chlorophyll in the Arabian Sea, the domain chosen for the study is bounded by 40⁰E and 78⁰E Longitude, and Equator and 30⁰N Latitude.

CHAPTER II

TOOLS FOR STUDY

Remote sensing

Remote sensing is the technology of acquiring data through a device which is located at a distance from the object without any physical contact, and analysis of the data for interpreting the physical attribute of the object. Both these aspects are intimately linked to each other.

The basic principle of the Remote Sensing method is that in different wavelength range of the electromagnetic spectrum each type of object reflects or emits a certain intensity of light. Remote sensing data could be either analog or digital form of a phenomena in the real world. Data may be acquired through a variety of devices depending upon the object or phenomena being observed. Most remote sensing techniques make use of emitted or reflected electromagnetic radiation of the object of interest in a certain frequency domain (infrared, visible light, microwaves). This is possible due to the fact that the examined objects (plants, houses, water surfaces, air masses ...) reflect or emit radiation in different wavelengths and in different intensity according to their current condition. Some remote sensing systems use sound waves in a similar way, and others measure variations in gravitational or magnetic fields.

GIS (Geographic Information System)

A Geographic Information System (GIS) is an automated tool for assisting the capture, storage, management, analysis, display and retrieval of spatially displaced information. (Strelch et al, 1986).

GIS is defined as an information system that is used to input, store, retrieve, manipulate, analyze and output geographically referenced data or geospatial data, in order to support decision making for planning and management of land use, natural resources, environment, transportation, urban facilities, oceanography, and other administrative records. GIS can be adapted to the marine environment also.

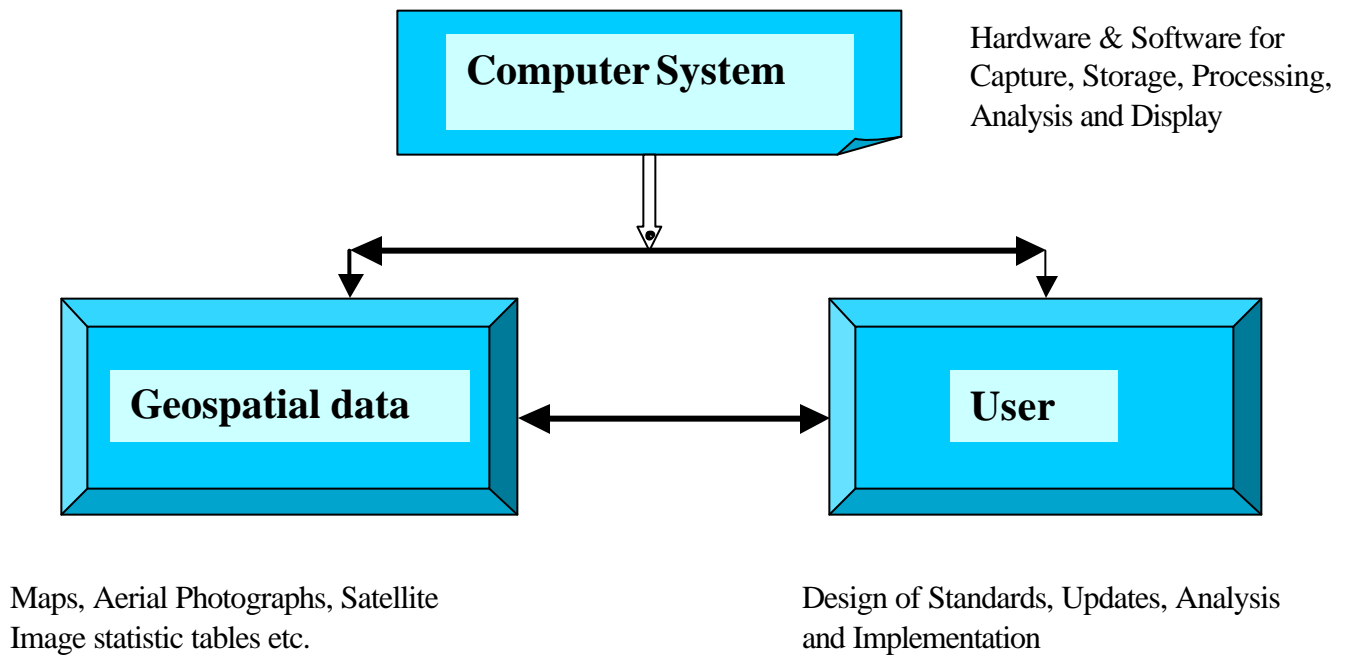


Fig-1. Key Component of GIS

. Marine and Coastal Geographical Information Systems focuses on the potential and progress of GIS research in the marine and coastal realm. GIS development enters into a highly dynamic environment where almost everything moves or changes. Marine GIS is called upon to describe the intimate relations among the wind and sea current that trigger certain oceanographic process and explain the impact of these processes to the behavior of marine organism, taking species biology and ecology into consideration, as well.

GIS is a complex tool that requires careful planning and design to be successfully implemented. Choice in hardware, software and data must be based on evaluation of project objectives, analytical requirements, data availability and data development considerations. Datasets must be evaluated and documented with metadata. The various steps in data transformations and GIS data analysis is shown in fig. 2.

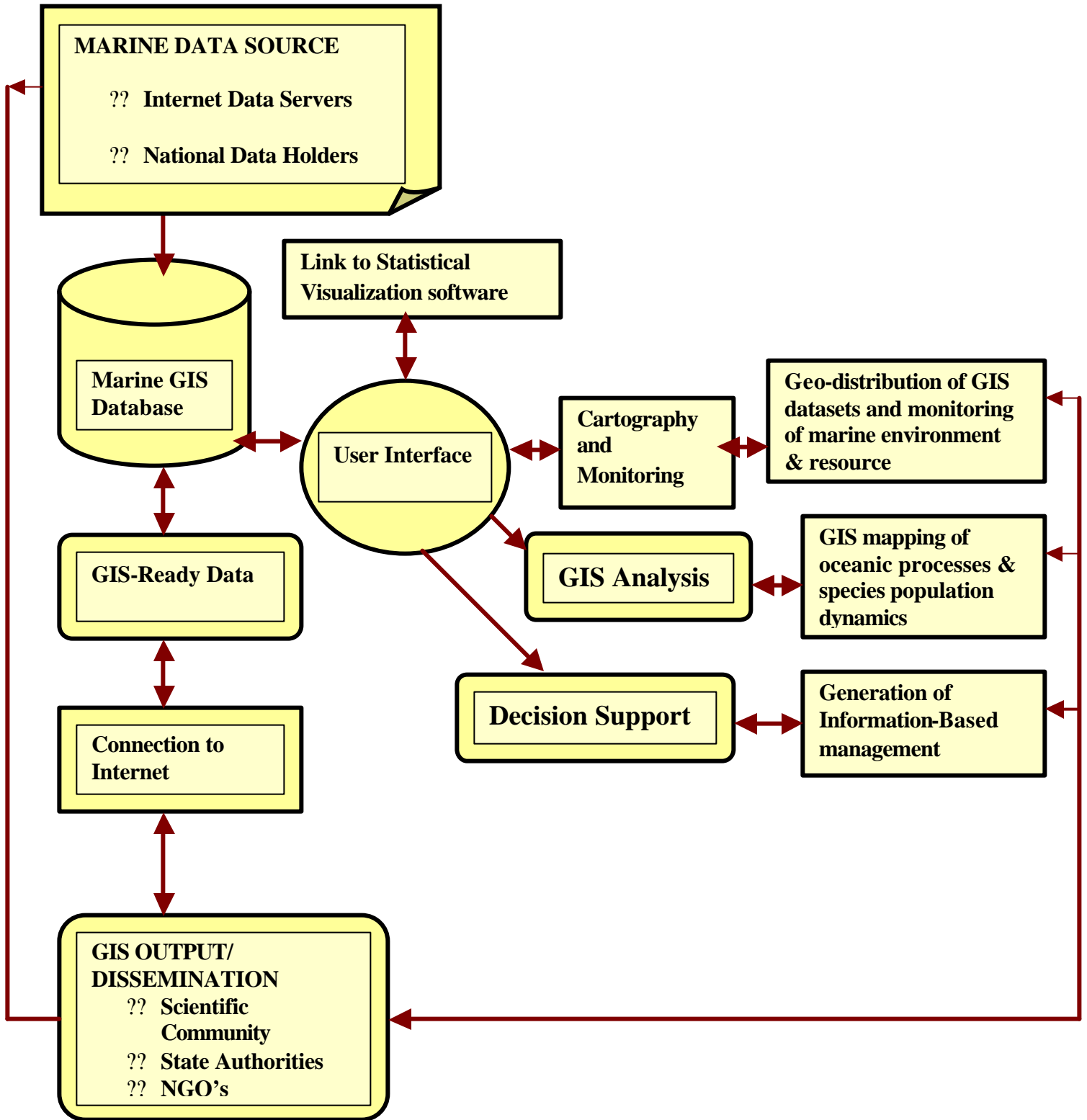


Fig-2. Conceptual Model of Marine GIS Development

Global Positioning System (GPS)

GPS stands for global positioning system, a system that has been established and is managed by the U.S.A in 1973 . The GPS system utilizes satellites that have been put into orbit that help people determine their exact positioning on the planet—whether it be for the purposes of navigation, for the purposes of military uses, or any type of enterprise that requires an exact global positioning by latitude, longitude and altitude. In fact, sometimes GPS systems are installed in vehicles, and some are installed in fishing boats. Finally, some GPS systems are fixed into position wherever they are installed, while some are portable.

GPS technology is essential for georeferencing. Attributing location to marine data is mandatory to GIS analysis and gives a meaning to the term ‘geography’ of the oceans. GIS constitutes the natural framework in which geospatial data could be stored and analysed and it is GPS that provides that essential information of geolocation to Remotely Sensed data and surveyed data.

Applications of Remote Sensing , GIS & GPS

In the marine context, GIS development enters into a highly dynamic environment where almost everything moves or changes. Marine GIS is called upon to describe the intimate among the wind and sea current that trigger certain oceanographic process and explain the Impact of these process to the behaviors of marine organism, taking species biology and ecology into consideration, as well. GIS contribute to the enhancement of natural resource monitoring and test the efficiency of currently applied management policies by presenting integrated product that describe the relation among biotic and abiotic resources and their current management schemes.

Meaden (2000) identified three new major components that are added to fisheries GIS application: 1. The vertical dimension 2. The dynamics of marine processes (upwelling, gyres, fronts, etc.). 3. The dynamics of marine objects. (Species populations).

Marine GIS include a wide area of applications, in this field it may be categorized as coastal, oceanographic and fisheries GIS, with a good deal of overlap among all three main kind of marine GIS.

Marine GIS must transfer into its computerized environment existing knowledge from many marine disciplines, such as marine geology, physical and biological oceanography and use data from related technologies, such as Remote Sensing (RS) and Global Positioning System (GPS).

CHAPTER III

Data and Methodology

Data used

Remote sensing data on sea surface temperature (SST), chlorophyll pigment concentration, sea surface winds and sea surface height anomaly from January 2002 to December 2005 were used for the present study. Table 1 gives the details pertaining to each of the data used in this study.

Table 1. Details pertaining to the remote sensing data used for the study including sensor, Resolution and data source.

Parameter	Sensor	Resolution	Web site
Sea surface temperature (SST)	Modis Aqua	Monthly data at 0.33-degree resolution	http://oceancolor.gsfc.nasa.gov/ , http://poet.jpl.nasa.gov/
Chlorophyll pigment concentration	SeaWifs (Sea Viewing wide field of view sensor)	Monthly data at 0.33-degree resolution	http://reason.gsfc.nasa.gov/OPS/Giovanni/ocean.seawifs.shtml
Sea surface wind	Quikscat (Quick Scatterometer)	Daily wind data at 0.25-degree spatial resolution	http://www.ssmi.com/qscat/qscat_browse.html , http://poet.jpl.nasa.gov/
Sea surface height (SSH)	Topex/Posidon and ERS-1/2 satellites	7-day snap-shots of the merged sea-level anomalies at 0.33 degree resolution	http://las.aviso.oceanobs.com

Sea surface temperature (SST)

Sea surface temperature is the water temperature at the surface. In practical terms, the exact meaning of "surface" will vary according to the measurement method used. A satellite radiometer "sees" a skin temperature representing the top millimeter; a thermometer in the ocean would see approximately the top 1 meter below the sea surface; the measurements routinely made from ships are often from the engine water intakes and may be 5m below the surface.

Since the 1980s satellites have been increasingly utilized to measure SST and have provided an enormous leap in our ability to view the spatial and temporal variation in SST. The satellite measurement is recorded by sensing the ocean radiation in two or more wavelengths in the infrared part of the electromagnetic spectrum which can be then be empirically related to SST. These wavelengths are chosen because they are,

1. within the peak of the blackbody radiation expected from the earth and
2. able to transmit well through the atmosphere

The satellite measured SST provides both a synoptic view of the ocean and a high frequency of repeat views, allowing the examination of basin-wide upper ocean dynamics not possible with ships or buoys. In SST measurements, the radiation emanates from the top "skin" of the ocean, approximately the top 0.1 mm or less, it may not represent the bulk temperature of the upper meter of ocean primarily due to the effects of solar surface heating in the daytime, and back radiation and sensible heat loss at night as well as from the effects of surface evaporation. This makes it difficult to compare to measurements from buoys or shipboard methods, complicating ground truth efforts. Secondly, the satellite cannot look through clouds, creating a "fair weather bias" in the long term trends of SST, these difficulties are small compared to the benefits in understanding gained from satellite SST estimates.

Sensor for SST

MODIS Aqua

Aqua, Latin for water, is a NASA Earth Science satellite mission named for the large amount of information that the mission will be collecting about the Earth's water cycle, including evaporation from the oceans, water vapor in the atmosphere, clouds, precipitation, soil moisture, sea ice, land ice, and snow cover on the land and ice. Additional variables also being measured by Aqua that include radiative energy fluxes, aerosols, vegetation cover on the land, phytoplankton and dissolved organic matter in the oceans, and air, land, and water temperatures.

The Aqua mission is a part of the NASA-centered international Earth Observing System (EOS). Aqua was formerly named EOS PM, signifying its afternoon equatorial crossing time. A timeline of Aqua on-orbit progress through the initial 120-day checkout period can be found [here](#).

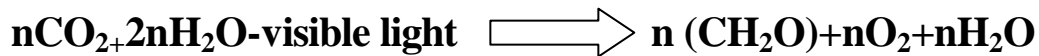
The MODIS (Moderate Resolution Imaging Spectroradiometer) instrument provides high radiometric sensitivity (12 bit) in 36 spectral bands ranging in wavelength from 0.4 μm to 14.4 μm . The responses are custom tailored to the individual needs of the user community and provide exceptionally low out-of-band response. Two bands are imaged at a nominal resolution of 250 m at nadir, with five bands at 500 m and the remaining 29 bands at 1,000 m. A ± 55 -degree scanning pattern at the Aqua orbit of 705 km achieves a 2,330-km swath and provides global coverage every one to two days. The data will be used to derive products ranging from vegetation, land surface cover, and ocean chlorophyll fluorescence to cloud and aerosol properties, fire occurrence, snow cover on the land, and sea ice cover on the oceans. The first MODIS instrument was launched on board the Terra satellite in December 1999.

Table 2. shows the characteristics of MODIS Aqua.

INSTRUMENT SPECIFICATIONS	
General Properties	<p>Continuous global coverage every 1 to 2 days. Daylight reflection and day/night emission spectral imaging. Polarization sensitivity less than 2% out to 2.2 μm. Absolute irradiance accuracy of 5% for bands below 3 μm and 1% for longer wavelength bands. Signal-to-noise ratios 838:1 (443 nm), 754:1 (531 nm), and 516:1 (869 nm) at 70° solar zenith angle.</p>
Swath dimensions	2300 km at 110° ($\pm 55^\circ$) from 705 km altitude
Power:	162.5 W (average), 225 W (peak)
Stability:	28 arcsec/sec
Data rate: (night)	6.2 Mbps (average), 10.5 Mbps (day), 3.2 Mbps
Instrument Instantaneous FOV	250 m (2 bands), 500 m (5 bands), 1000 m (29 bands)
MODIS home page:	http://modis.gsfc.nasa.gov

Chlorophyll Pigment Concentration

Chlorophyll is a green photosynthetic pigment found in most plants, algae, and cyanobacteria. Its name is derived from ancient Greek: *chloros* = green and *phyllon* = leaf. Chlorophyll absorbs most strongly in the blue and red but poorly in the green portions of the electromagnetic spectrum, hence the green color of chlorophyll-containing tissues like plant leaves. The overall photosynthesis processes may be represented by:



In coastal areas, runoff from rivers, resuspension of sand and silt from the bottom by tides, waves and storms and a number of other substances can change the color of the near-shore waters. Some types of particles (in particular, the cells of phytoplankton, also referred to as algae) can also contain substances that absorb certain wavelengths of light, which alters its characteristics

Satellite-borne radiometers also measure surface chlorophyll concentrations. In the ocean, light reflects off particulates suspended in the water, and absorption of light is mainly due to chlorophyll present in phytoplankton. Chlorophyll is very good at absorbing blue light, thus a high level of chlorophyll will reduce the availability of blue light. Radiometers measure radiance at different wavelengths, and these measured radiances may then be quantitatively related to various constituents in the water column. The satellite can detect very small changes in the ocean color as a result of the chlorophyll in phytoplankton. The basic principle behind the remote sensing of ocean color from space is that the more phytoplankton in the water, the greener it is; the less phytoplankton, the bluer it is.

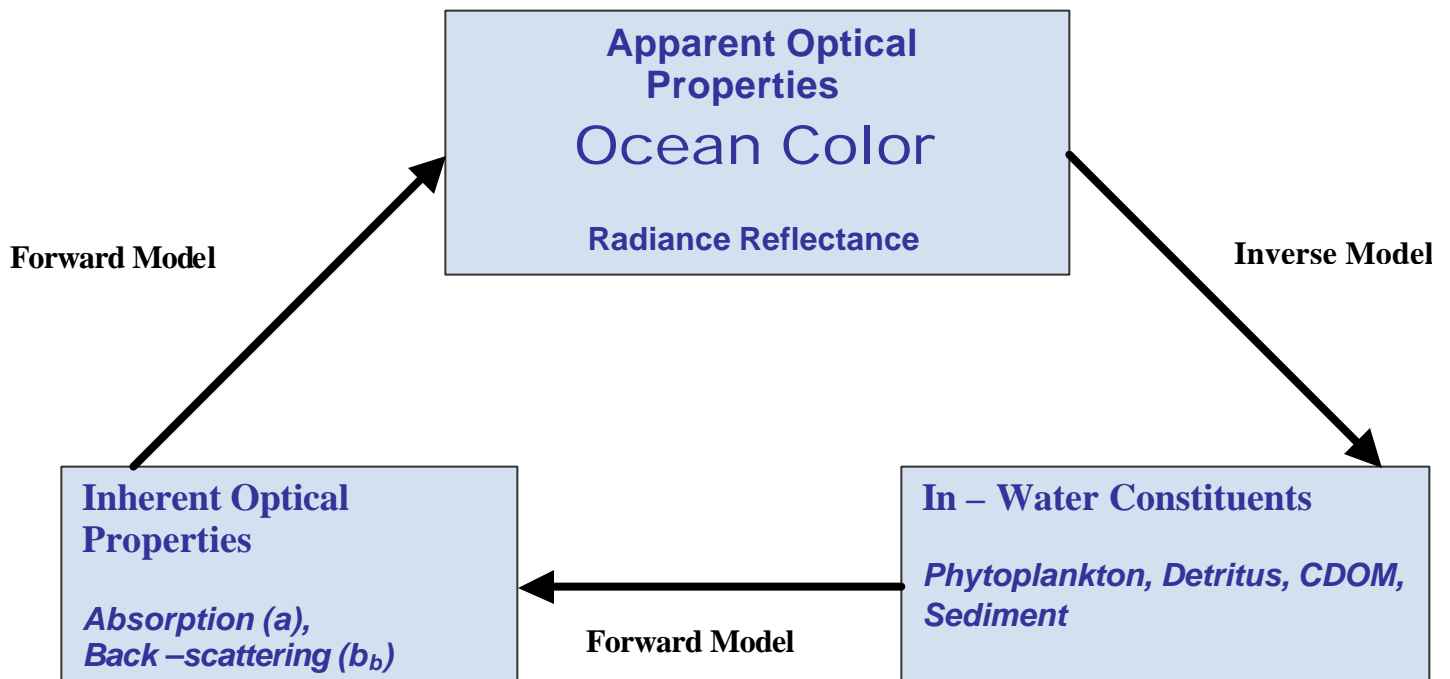


Fig-3. Schematics diagram showing the interrelationships between apparent optical properties such as ocean color, in –water constituents and inherent optical properties.

SeaWiFS

The purpose of the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) Project is to provide quantitative data on global ocean bio-optical properties to the Earth science community. Subtle changes in ocean color signify various types and quantities of marine phytoplankton (microscopic marine plants), the knowledge of which has both scientific and practical applications.

Table 3. Shows the characteristics of SeaWIFS.

Sea-viewing Wide Field-of-view Sensor	
AGENCY	NASA (USA)
SATELLITE	OrbView-2 (USA)
LAUNCH DATE	01/08/97
SWATH (km)	1100
RESOLUTION (m)	2806
# OF BANDS	8
SPECTRAL COVERAGE (nm)	402-885

Sea Surface Wind

Average speed of the air moving over the ocean surface, obtained by analyzing the strength of returning radar pulses. Wind speed as measured from an altimeter is an indirect measurement based on the small-scale roughness of the sea surface. Wind speed is measured from the strength of the returned signal in the time following the first return from the surface. A windless sea is smooth on small, say a few centimeters, even if it is rough on the scale of swell; such a sea will have a returned signal that is short in duration because it comes only from the center of the transmitted pulse. If there is a wind, the sea will be rough on the small scales, and there will be signal returned from the parts of the ocean not directly beneath the satellite; that is, as the outer part of the incident pulse strikes the ocean well away from the point of first encounter, some signal is scattered, by the small scale wavelets, back to the satellite, and this energy arrives after the first returns. Consequently the strength of the signal following the main return is a measure of the wind speed at the sea surface. There is a reliable relationship between the energy scattered from near nadir and the wind speed.

The **QuikSCAT** (Quick Scatterometer) is an earth-observing satellite that provides wind speed and direction information over oceans to NOAA. It is a "quick recovery" mission to fill the gap created by the loss of data from the NASA Scatterometer (NSCAT) that was lost in June 1997. It is in a sun-synchronous low-earth orbit.

NASA's Quick Scatterometer (QuikSCAT) was lofted into space at vehicle from Space Launch Complex 4 West at California's Vandenberg Air Force Base. The satellite was launched in a south-southwesterly direction, soaring over the Pacific Ocean at sunset as it ascended into space to achieve an initial elliptical orbit with a maximum altitude of about 800 kilometers (500 miles) above Earth's surface. The Sea Winds instrument on the QuikSCAT satellite is specialized microwave radar that measures near-surface wind speed and direction under all weather and cloud conditions over Earth's oceans. SeaWinds uses a rotating dish antenna with two spot beams that sweep in a circular pattern. The antenna radiates microwave pulses at a frequency of 13.4 gig hertz across broad regions on Earth's surface. The instrument will collect data over ocean, land, and ice in a continuous, 1,800-kilometer-wide band, making approximately 400,000 measurements and covering 90% of Earth's surface in one day.

Table 4. shows the characteristics of QuikSCAT (Quick Scatterometer)

Product Name	Product Definition	Product Units	Spatial Resolution	Temporal Resolution	Coverage Area	Period of Product Availability
Ocean Wind Vectors	An estimate of the speed and direction of winds over the global ocean	Wind direction units: degrees Wind Speed units: meters per second	25 km	Daily	Global	1999-present

Sea Surface Height

Sea surface height is defined as the distance of the sea surface above the reference ellipsoid. The sea surface height is computed from altimeter range and satellite altitude above the reference ellipsoid. The "reference ellipsoid" is the first-order definition of the

Non-spherical shape of the Earth as an ellipsoid of revolution with equatorial radius of 6378.1363 kilometers and a flattening coefficient of $1/298.257$. Sea surface height is often shown as a sea-surface anomaly or sea-surface deviation, this is the difference between the sea surface height at the time of measurement and the average sea surface height for that region and time of year.

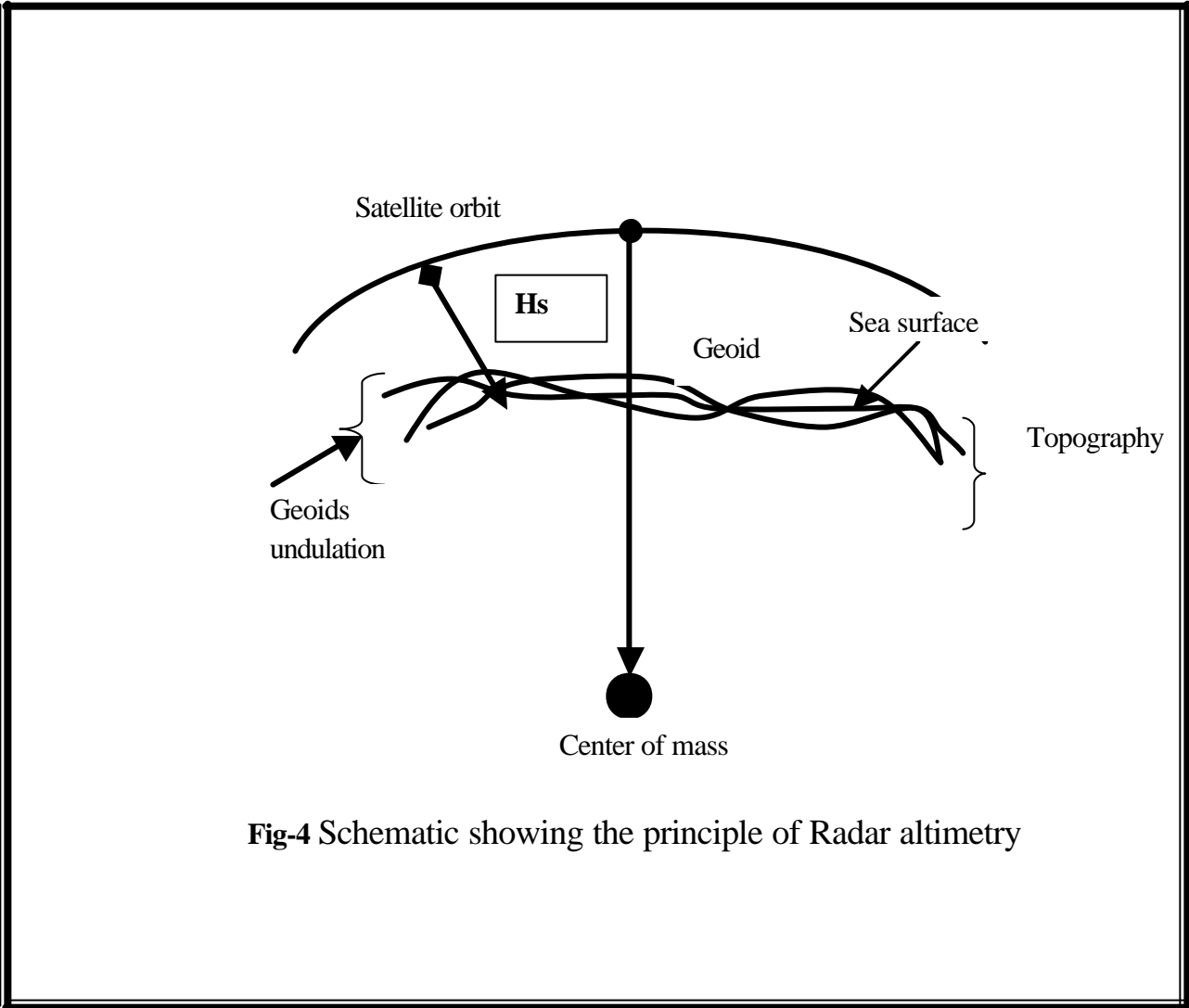


Fig-4 Schematic showing the principle of Radar altimetry

Table 5. shows the characteristics of Topex/Posidon and ERS-1/2 satellites

Topex/Posidon and ERS-1/2 satellites	
Lunch data	August 10, 1992
Altitude, Km	1336
Inclination	066.0362°
Perigee Height:	1,331 km
Inclination	66.0
Period, min	112
Mean Anomaly at Epoch	093.0175°
Ground track equatorial spacing, Km.	316
Longitude of equator crossing, deg	99.947
Cycle 1 start date	September 23, 1992 (3:38 UTC)

Methodology

The digital remotely sensed data on various oceanic parameter such as SST, chlorophyll pigment concentrations, sea surface height and sea surface winds were extracted for further processing using GIS technique.

Processing of Remote Sensing Data in GIS Environment

Various steps involved in the processing of remote sensing data in the GIS environment are listed below.

PARAMETERS

- ✍✍ SST from Modis Aqua/Terra
- ✍✍ SSH from Topex/Posidon and ERS1/2
- ✍✍ SSW from Quikscat
- ✍✍ Chlorophyll Concentration from SeaWifs

GIS ENVIRONMENT

- ✍✍ Arc View 3.3
- ✍✍ ArcGIS 8

STEPS

- ✍✍ Create Shape File
- ✍✍ Create Surface Area of Arabian Sea by Digitization
- ✍✍ Using Inverse Distance Weighting Method
- ✍✍ Export to Vector Format
- ✍✍ Create Contour of SST, SSH, SSW, Chlorophyll Concentration

ANALYSIS

- ✍✍ Seasonal Variation and Distribution
- ✍✍ Inter-annual variation and Distribution

RESULT

GIS environment

ArcGIS is the name of a group of Geographic Information System software product lines produced by ESRI., ArcGIS is an integrated collection of GIS software products for building a complete GIS. ArcGIS enables users to deploy GIS functionality wherever it is needed in desktops, servers, or custom applications; over the Web; or in the field.

ArcView allows one to view spatial data, create maps, and perform basic spatial analysis. ArcEditor which includes all the functionality of ArcView, includes more advanced tools for manipulation of shapefiles and geodatabases; or ArcInfo the most advanced version of ArcGIS, which include added capabilities for data manipulation, editing, and analysis. There are also server-based ArcGIS products, as well as ArcGIS products for PDAs.



Fig-5. Block diagram showing the platform of ArcGIS

In general, the processing using GIS can be divided into three parts - data conversion, contour map generation and analysis.

Data conversion - In this step, ASCII data is first converted in the dbf format for the GIS environment analysis using MS Access and MS Excel.

Contour Map Generation

All the tasks such as generation of contour maps were carried out using ARC/GIS version 9.0 and Arc/View 3.3. Subsequently, point map (shape files) of each of the 4 parameters were carried out in GIS environment. Inverse distance weighted method was used for the creation of filled contour maps of all the parameters.

Shape File

Shape file are a simple, non-topological format for storing the geometric location and attribute information of geographic feature. The Shape file format defines the geometry and attribute of geographical – referenced feature in as many with specific extension that must be stored in the some project workspace.

Digitization

Digitizing is the process of encoding geographic feature in digital form as x, y coordinates, and it is carried out in order to create spatial data from existing hard copy of maps and documents.

Inverse distance weighting interpolation method (IDW)

IDW interpolation explicitly implements the assumption that things that are close to one another are more alike than those that are farther apart. To predict a value for any unmeasured location, IDW will use the measured values surrounding the prediction location. Those measured values closest to the prediction location will have more influence on the predicted value than those farther away. Thus, IDW assumes that each

measured point has a local influence that diminishes with distance. It weights the points closer to the prediction location greater than those farther away, hence the name inverse Distance weighted.

Analysis

Analysis of the seasonal and inter-annual variability of the Arabian Sea using filled contour maps was carried out and the parameters involved discussed

CHAPTER IV

Result & Discussion

Study of Seasonal cycle

To understand the seasonal cycle, the monthly mean data for January, April, July, August, and October for the year 2002 was used.

Seasonal cycle of sea surface temperature

Sea surface temperature distribution in January showed a pattern, which was more or less uniform in the zonal direction, but varied meridionally. SST was coldest in the northwestern Arabian Sea with a minimum of 20°C and increased steadily towards south where the maximum was 28°C. Thus, the north-south SST gradient was 8°C. In April, the SST showed a rapid heating of 6°C in the north, while it was 3°C in the south compared to winter. The spatial variation in April was 4°C, from 26°C in the north to 31°C to the south. In July, as the summer monsoon sets in the pattern of SST distribution changed from zonal to meridional. Coldest waters of 26°C occurred along the western margin off Somalia and Arabia, while warmest waters of 30°C was encountered in the southeastern region. Colder waters of 27°C occurred along the southern part of the west coast of India. This indicated the signal of upwelling. In August the western Arabian Sea as well as the southern part of the west coast of India further cools increasing the thermal gradient of the basin to 4°C .which is 1°C colder, compared to July. This cooling is because of the continued upwelling and off shore advection of upwelled water with time. In October, Arabian Sea becomes uniformly warmer with SST varying marginally from 29 to 30°C .However, the coastal region of Somalia, Arabia and part of the Gujarat and Pakistan showed SST of 27-28°C.

In summary, the seasonal cycle of SST in the Arabian Sea showed two periods of warming during April and October and two periods of cooling coinciding with summer and winter monsoons. The cooling of SST during summer was due to upwelling of colder waters while cooling during winter was due to reduced solar heating.

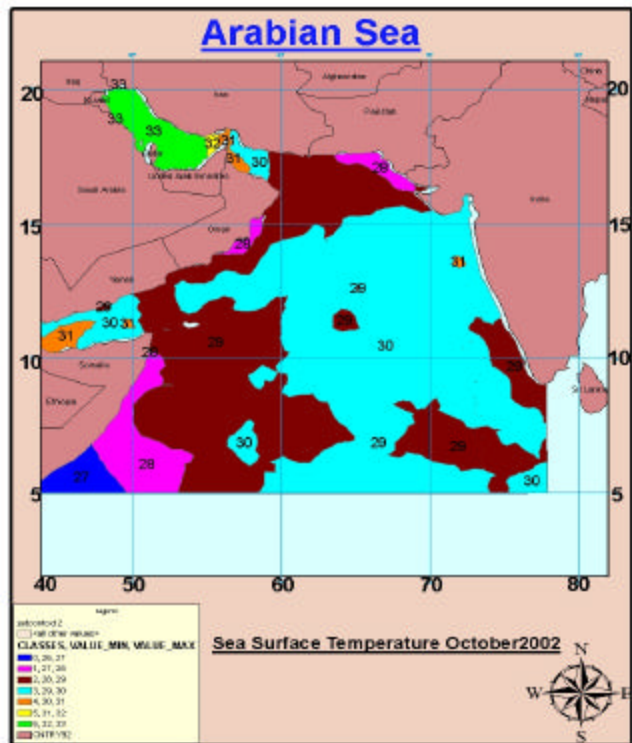
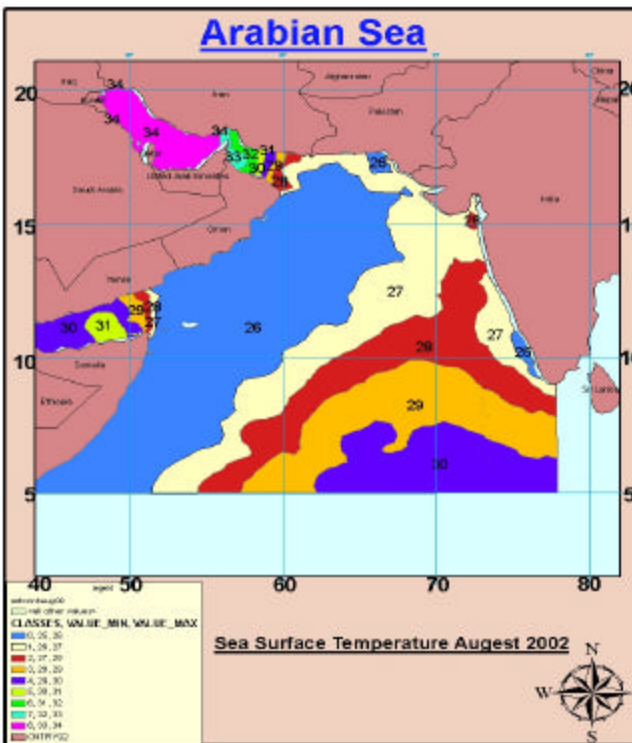
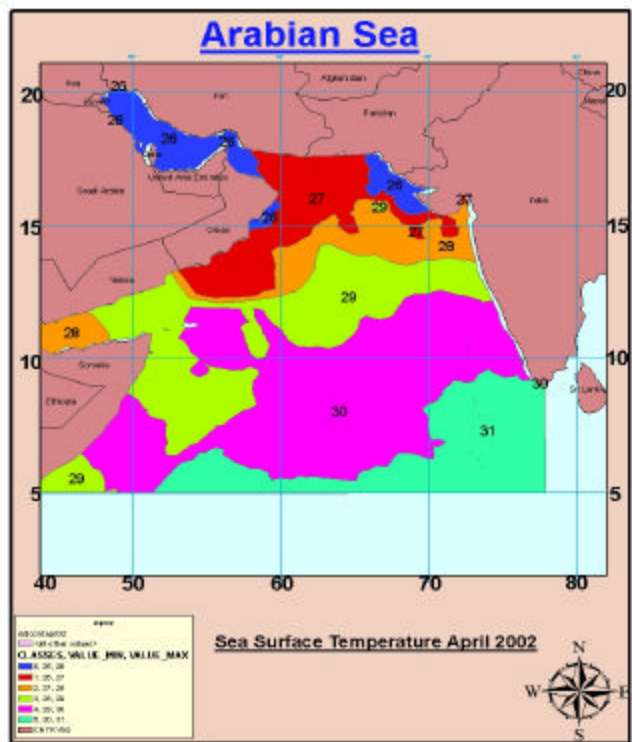
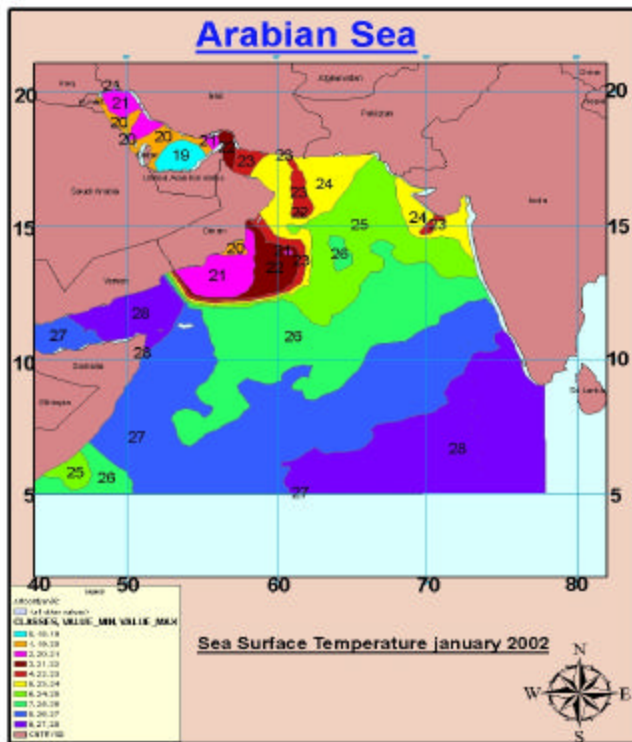


Fig-6. Seasonal cycle of sea surface temperature

Seasonal cycle of chlorophyll pigment concentration

Chlorophyll pigment concentration during January varied from 0.2 to 0.5 mg/m³ in the Southern Arabian Sea, south of 12°N. Towards the north the chlorophyll pigment concentration showed a steady increase from 0.5 to 1mg/m³. However, in the coastal region along the northern part of the west coast of India, coast of Pakistan, and Somalia the chlorophyll concentrations increased up to 5 mg/m³. The very high pigment concentration of 10-15 mg/m³ was noticed in isolated pockets in the Gulf of Kutch. In April almost the entire Arabian Sea showed very less chlorophyll concentration of 0.2 mg/m³. However, the northern Arabian Sea showed a gradual increase from 0.3 to 5 mg/m³, the higher values were close to the coastal regions of India, Pakistan and Arabia. In July, the chlorophyll distribution showed a meridional pattern similar to that of SST, with very high concentrations along the western and eastern margins of the Arabian Sea. The values increased from 0.5 mg/m³ in the off shore region to 15 mg/m³ close to the coast. The regions of high chlorophyll concentration coincide with the upwelling region such as Somalia, Arabia and the west coast of India. In August, the chlorophyll distribution pattern remained similar to that of July, except that the region of ~0.5mg/m³ chlorophyll concentrations advected further offshore. The chlorophyll concentrations along the west coast of Indian during October were between 3 to 10 mg/m³ very near to the coast. Along the western boundary, in the offshore region the chlorophyll concentrations showed a decrease compared to August with values between 0.3 to 0.5 mg/m³. However, very near to the Somalia coast the maximum concentration was 2 mg/m³ while that near the Arabia was 3 to 10 mg/m³.

In summary, the chlorophyll concentrations were highest during summer and winter, and lowest in April. The highest concentrations in summer, July-August, was due to the upwelling along the coasts of Somalia, Arabia and the west coast of India, and the advection of upwelled water offshore. As a result most part of the Arabian Sea becomes biologically productive. In winter the high chlorophyll concentrations in the northern Arabian Sea is due to the winter cooling and convective mixing. The lowest chlorophyll in April is due to the high stratification because of high SST.

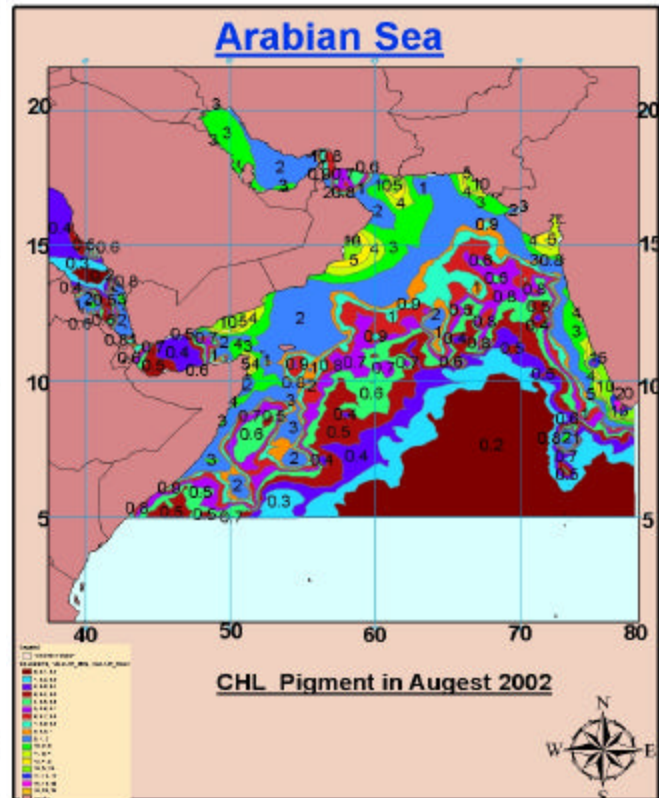
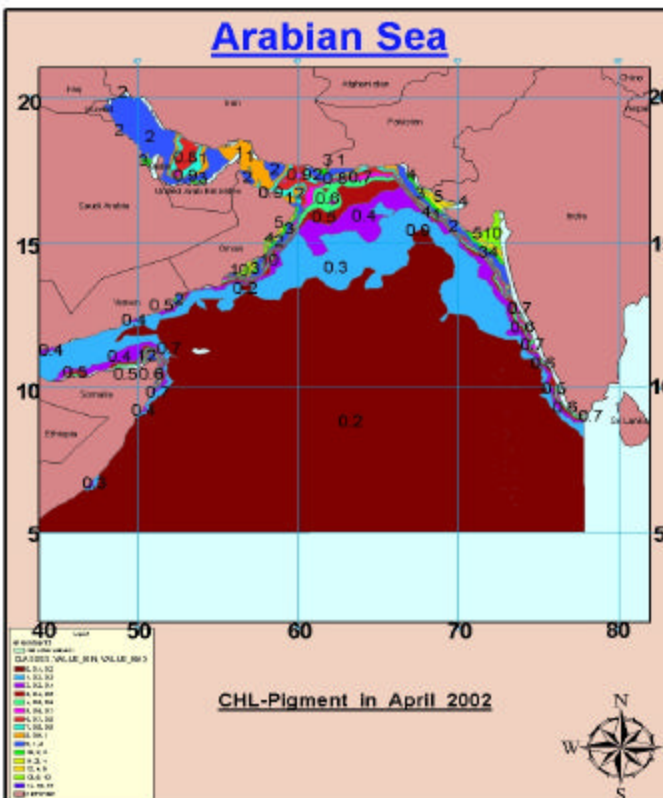
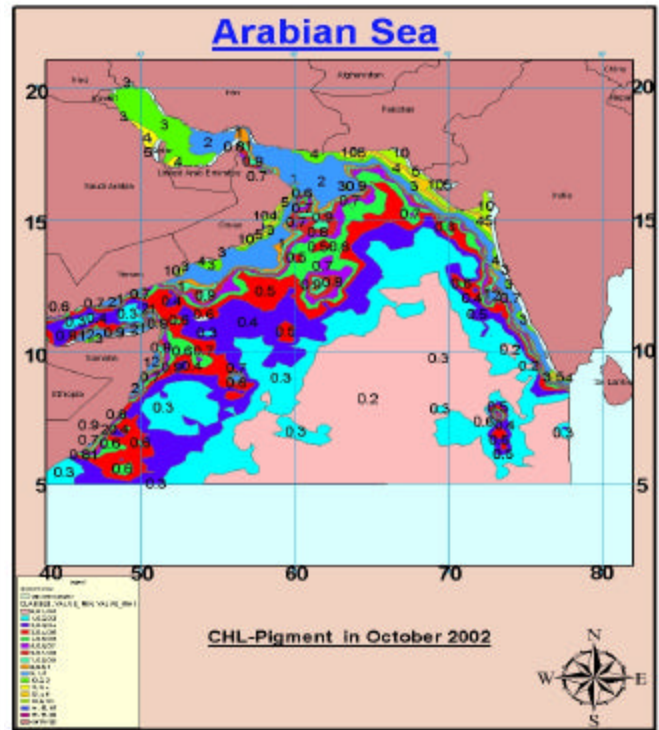
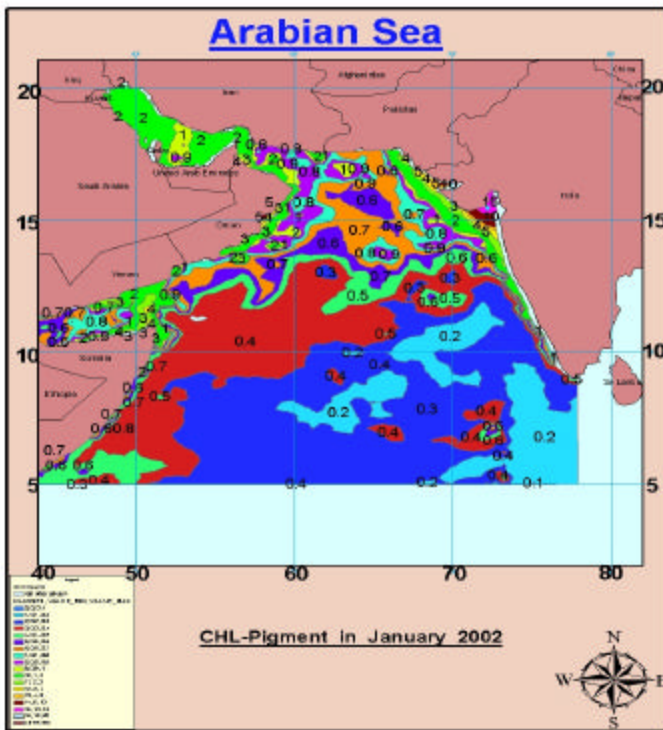


Fig-7. Seasonal cycle of chlorophyll pigment concentration

Seasonal cycle of sea surface height (SSH)

The sea surface height (SSH) anomaly in January is positive along the coastal boundary indicating a northward current along the west coast of India and southward current along the coast of Arabia and Somalia. In the open ocean region the SSH anomaly was negative. But we also notice a positive SSH anomaly extending from southern part of the west coast of India, which is linked, to Rossby wave propagation. In April the positive SSH anomaly occupies the entire basin. In July negative SSH anomaly occupies the coastal regions along the basin, except in the northern tip of Somalia, which has negative SSH anomaly of 20cm. The negative SSH anomaly along the western boundary shows that the currents are toward the north, that is the Somali current, which will induce upwelling. The coastal current along the west coast of India is towards south. The central and southern Arabian Sea has positive SSH anomaly. The SSH anomaly pattern in August remains similar to that of July but we see the offshore spreading of negative SSH anomaly from the southern part of the west coast of India which is the signature of Rossby wave propagation. In October we see alternate bands of negative and positive SSH anomaly in a zonal direction in the south but becomes meridional towards the north. A strong positive SSH anomaly is seen off shore of the tip of Somalia indicates the presence of Socotra eddy.

In summary, we see two types of circulation in the basin of Arabian Sea – a counter clockwise circulation during winter with northward moving West Indian coastal current (WICC) along the Indian coast and southward moving current along the Arabia and Somalia coast. In summer a clock wise circulation occurs in the Arabian Sea with strong Somali current moving towards north along the western boundary and a southerly current along the west coast of India, the WICC. In both the seasons we notice a westward extension of positive (winter)/negative (summer) SSH anomaly from the southern part of the west coast of India indicating the propagation of Rossby wave.

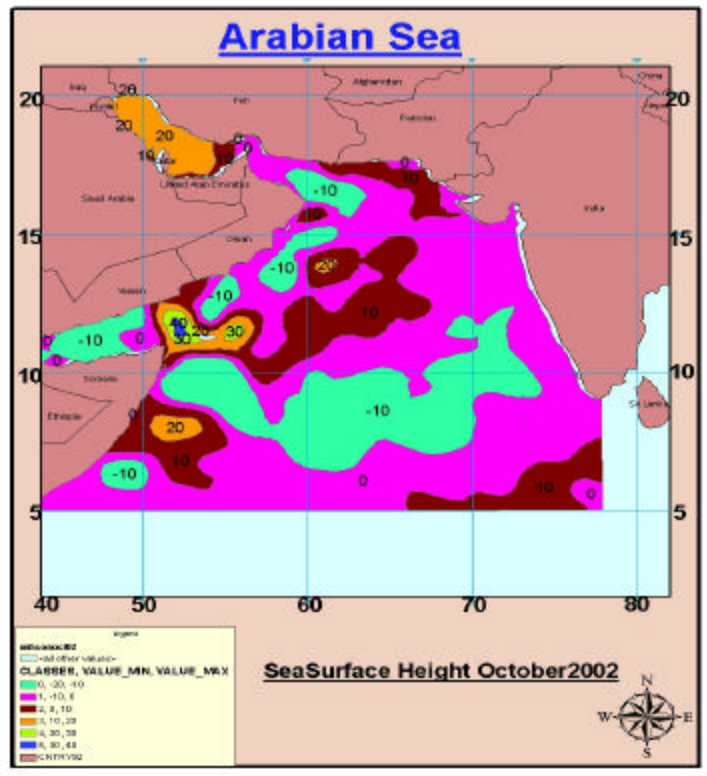
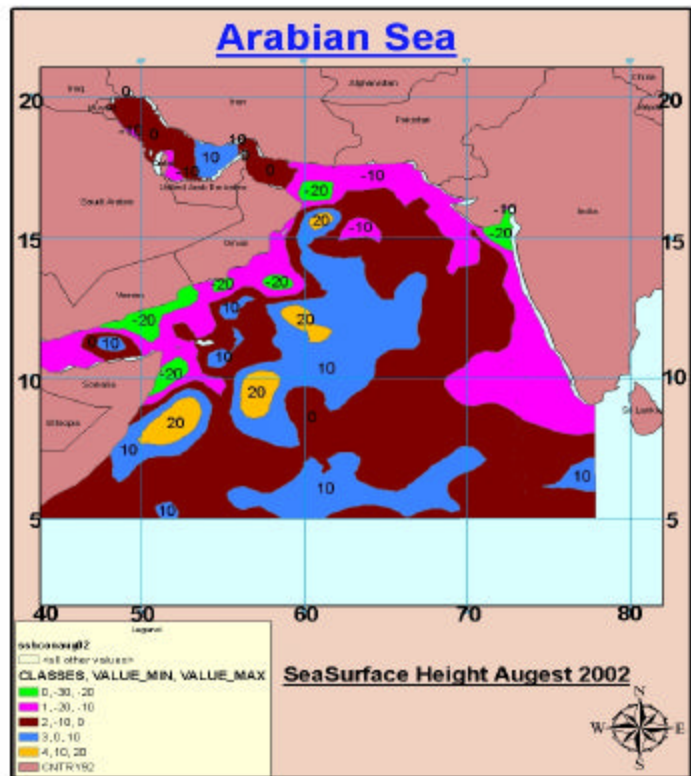
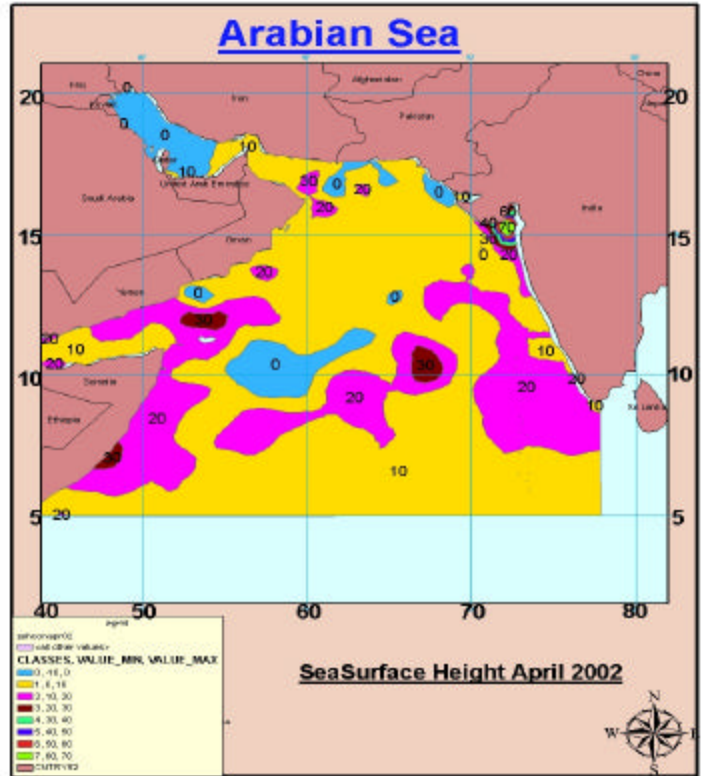
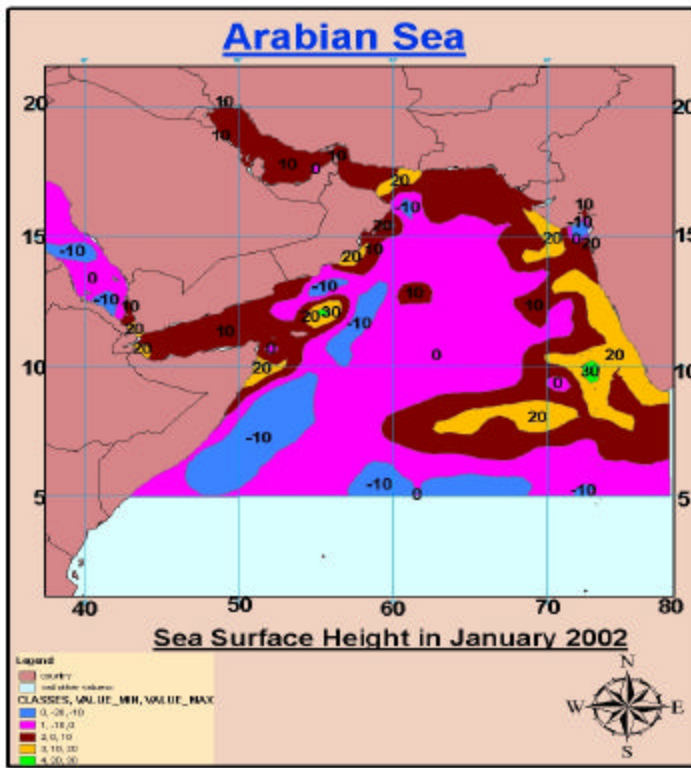


Fig- 8. Seasonal cycle of sea surface height

Seasonal cycle of sea surface wind

The winds during January are northeasterly with a speed of 5-6m/s in the entire basin of Arabian Sea, except in a small region close to west coast of India where it is northwesterly (Fig. Not presented). The wind in April was southwesterly in the southwestern part of the Arabian Sea, while in northeasterly in the rest of the Arabian Sea. But both the winds were weaker. In July strong southwesterly winds occupy most part of the Arabian Sea except very near the southern part of peninsular Indian, where it is northwesterly. The speed of southwesterly wind was about 15m/s. In August, the wind pattern remains more or less same but change in the wind speed. In October the wind pattern showed a zonal distribution with southwesterly winds in the north and south with northeasterly wind in between them. Southwesterly winds in the south were strong, while the northeasterly and southwesterly in the north were weaker.

In summary, winter monsoon was characterized by northeasterly winds of ~5-6 m/s while the summer monsoon winds were southwesterly and strong ~15 m/s. During April winds were weaker and variable.

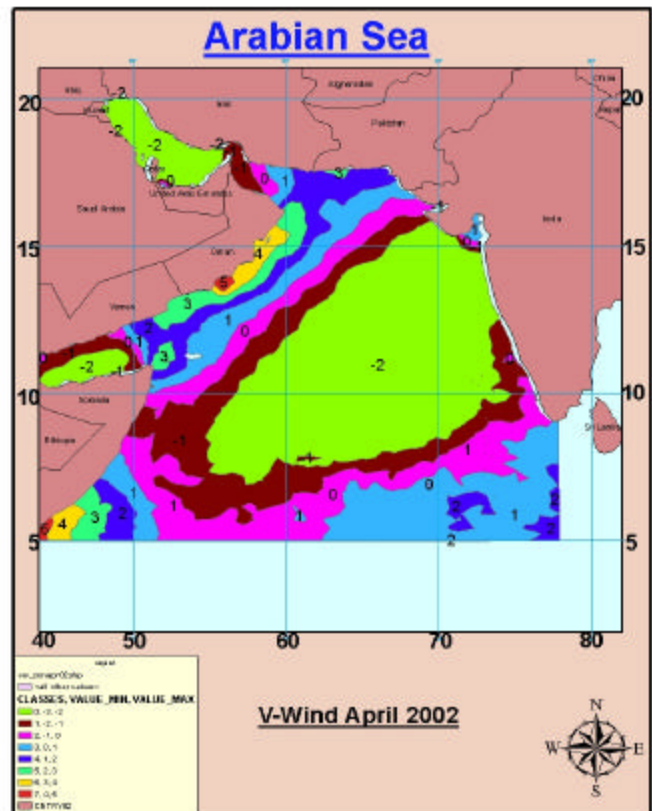
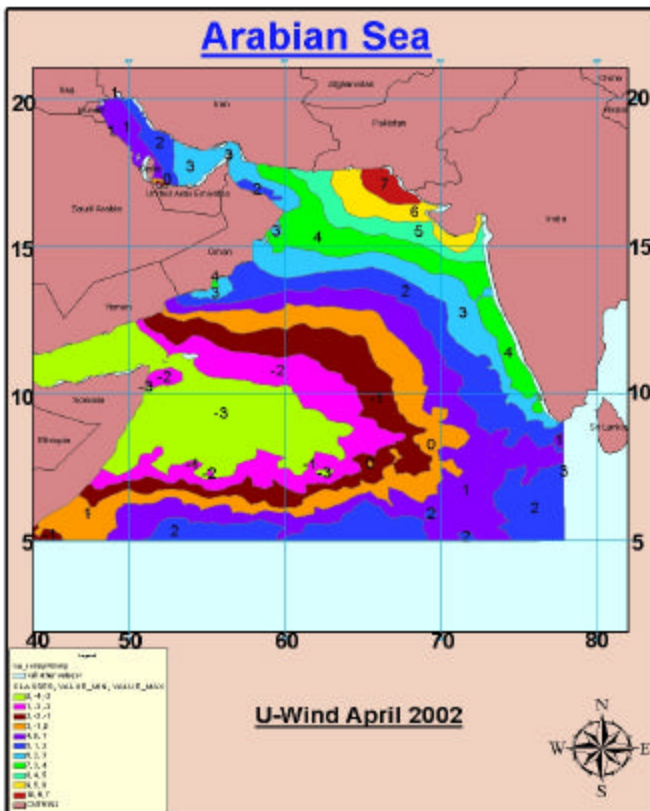
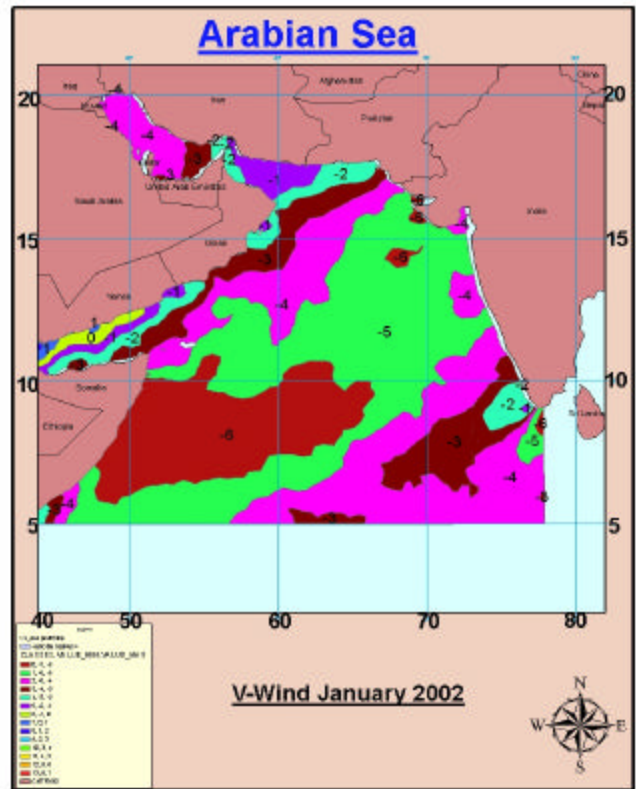
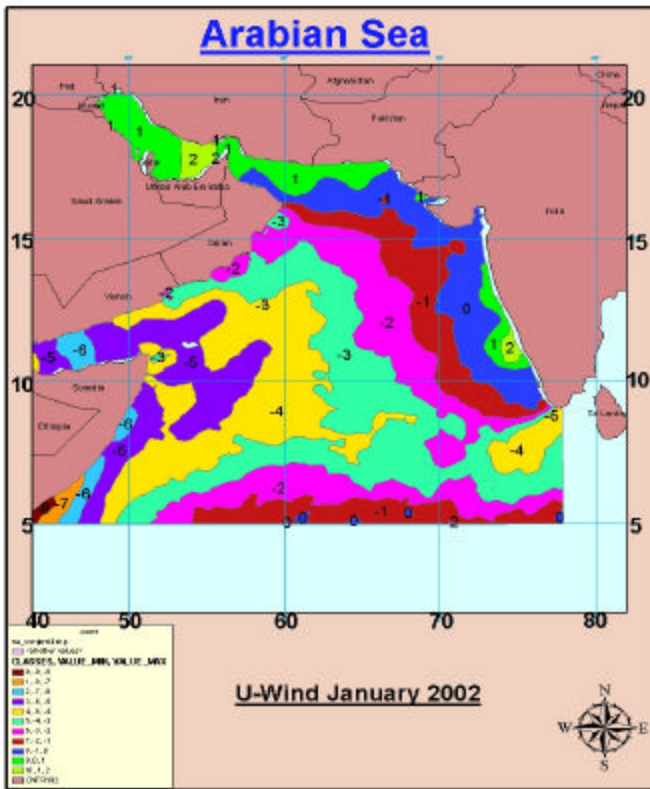


Fig-9. Seasonal cycle of sea surface

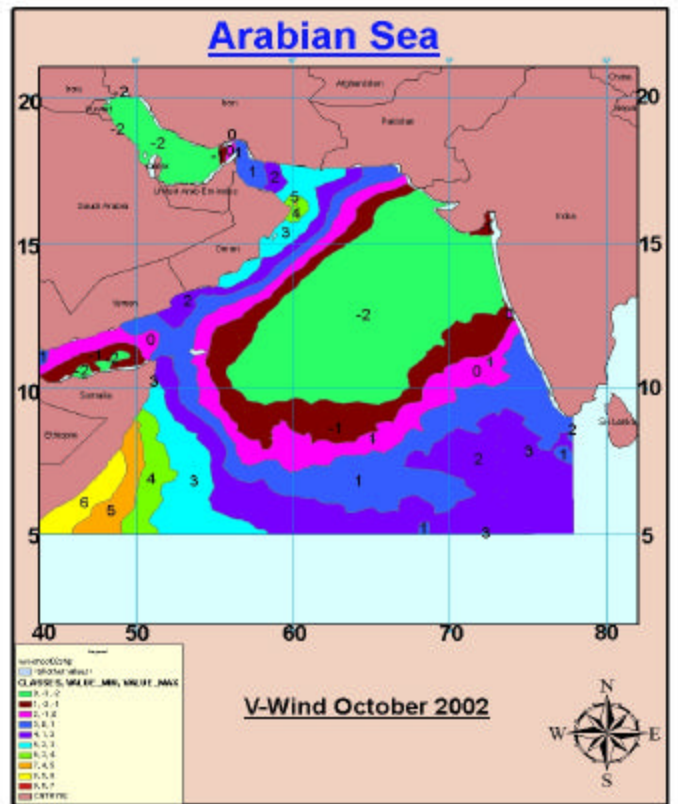
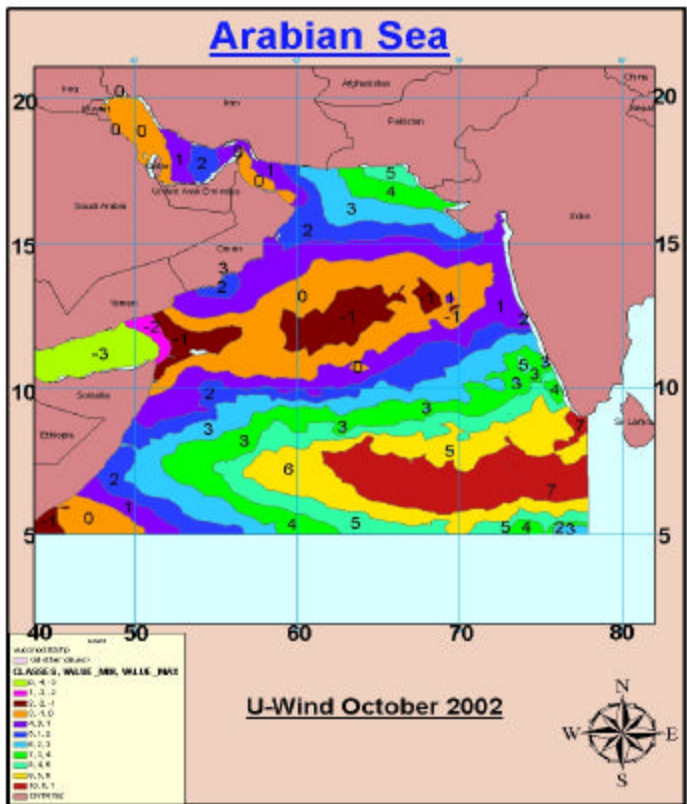
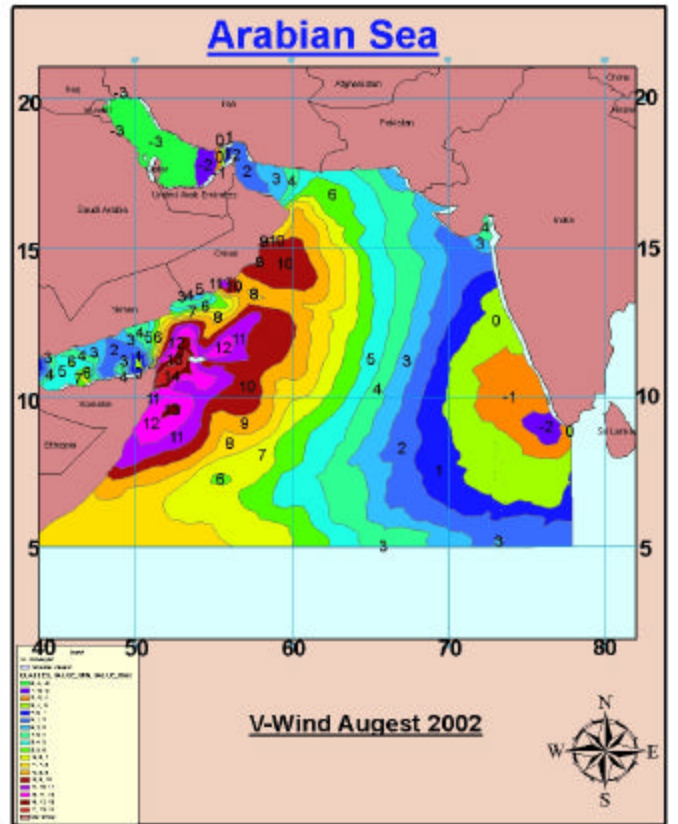
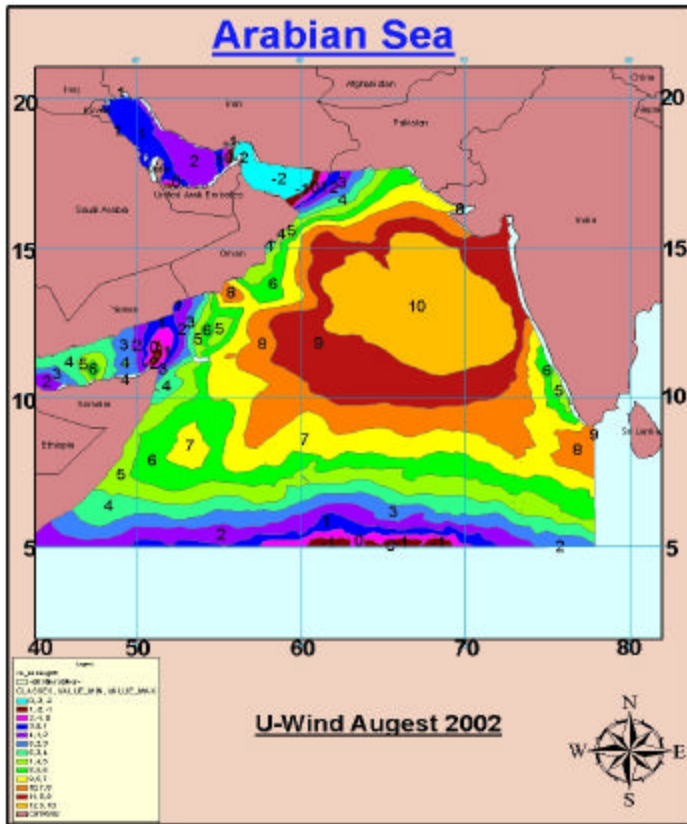


Fig-9. Seasonal cycle of sea surface wind

Inter-annual variability during 2002-2005

To understand the inter-annual variability we selected the month of January and August during 2002 to 2005. The reason for selecting January and August is the following. The month of January represents the peak winter, which is reflected in the property distribution such as SST, SSW, SSH, and chlorophyll pigment concentrations. Similarly, the analysis of seasonal variability showed that Chlorophyll concentration, SST and SSH showed maximum variability in the month of August, while SSW was strongest in July. Since the wind being the forcing for oceanic variability, and there exists time lag between the forcing and response, we thought it may be a good idea to choose the month of August to track inter-annual variability in chlorophyll concentration, SST and SSH while July for SSW.

January 2002-2005

Sea Surface Temperature

SST distribution during January 2002 showed a progressive cooling from south to north in the Arabian Sea from 28°C to 20°C. North of 15°N, SST was between 25°C to 22°C. In January 2003, SST in general was warmer in the Arabian Sea compared to January 2002 varying from 29°C in the south to 24°C in the north. The warming during 2003 was about 1°C in the south, while it was about 5°C in the north. The SST distribution during 2004 and 2005 were similar but compared to 2003 the northern most part was colder in 2004 and 2005 January. In summary the Arabian Sea was coldest in January 2002 and warmest in January 2003.

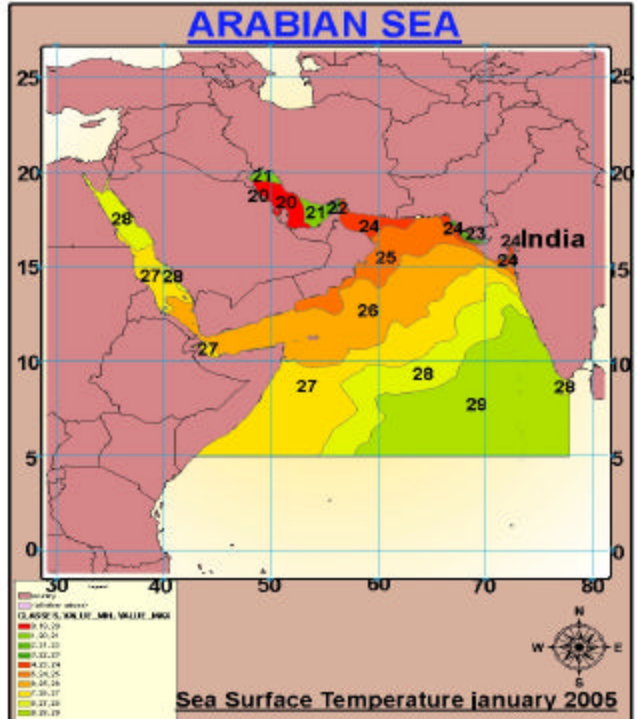
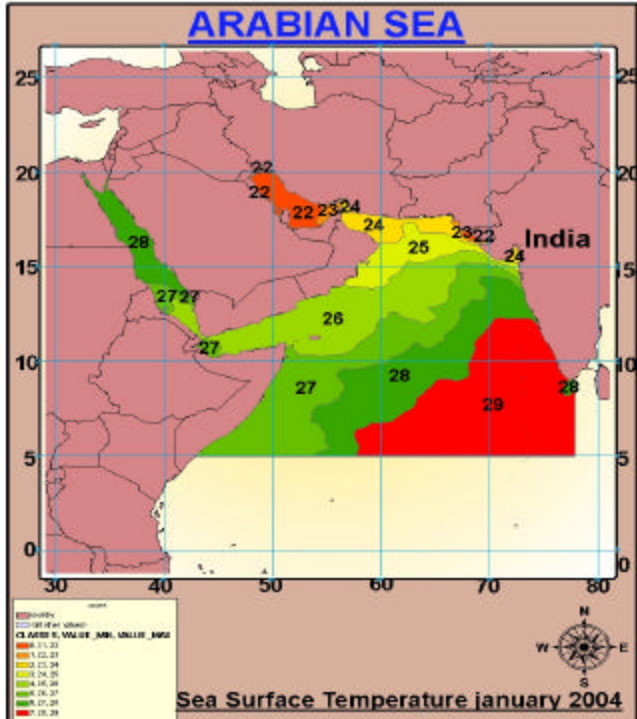
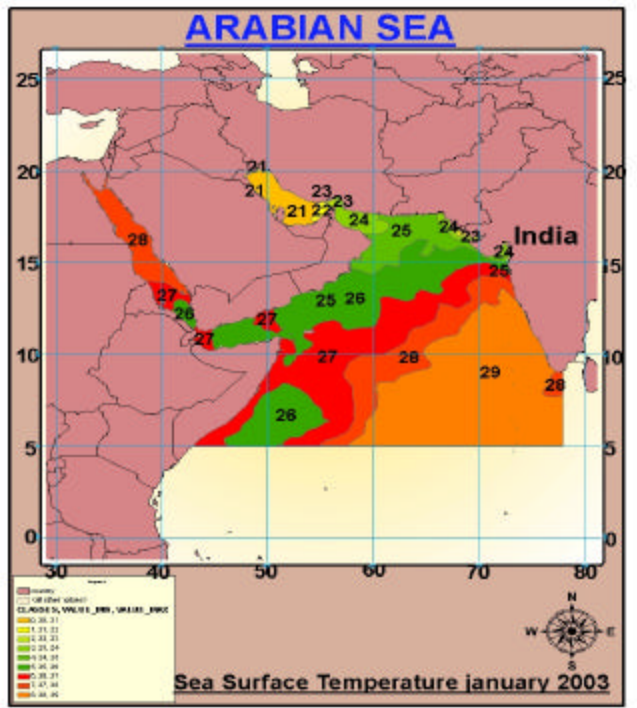
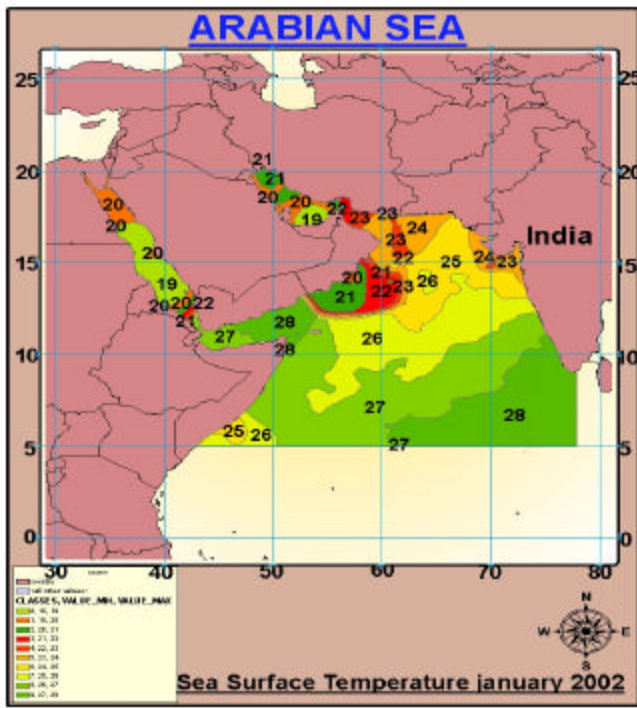


Fig-10. Inter-annual cycle of Sea Surface Temperature

Chlorophyll pigment Concentration

In January 2002 the chlorophyll pigment concentration was least in the southeastern Arabian Sea and showed steady increase towards west and north. North of 15°N, concentrations were in excess of 0.5 mg/m³ and in the coastal region along the northern part of the west coast of India, coast of Pakistan, and Somalia the chlorophyll concentrations increased up to 5 mg/m³. The very high pigment concentration of 10-15 mg/m³ was noticed in isolated pockets in the Gulf of Kutch. In January 2003, an overall increase in chlorophyll concentration was noticed in the northern as well as the western Arabian Sea. In the north it ranged between 0.5 to 2 mg/m³ where the 0.5 mg/m³ contour extends from western boundary into the central Arabian Sea. In January 2004 the chlorophyll concentration further increased in the north up to 3 mg/m³, while the concentration in the south decrease as could be seen from the contour of 0.5 mg/m³ near the western boundary which moved much closer. In January 2005, the chlorophyll concentrations were the least. In the north it varied between 0.5 to 1 mg/m³, while in the south it was between 0.2 to 0.5 mg/m³ in most of the region. Very close to the coast the values did not show much variability.

In summary, the chlorophyll pigment concentrations during January 2003 were the highest, while that in 2005 was the least.

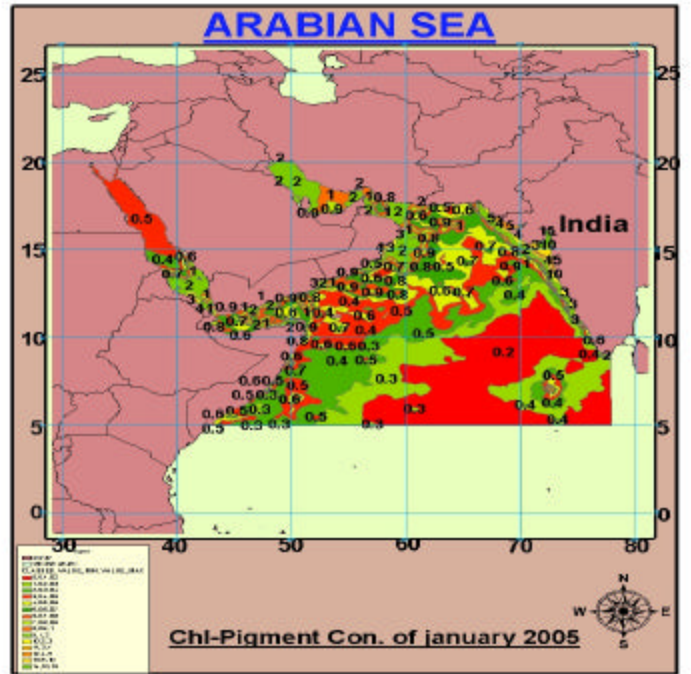
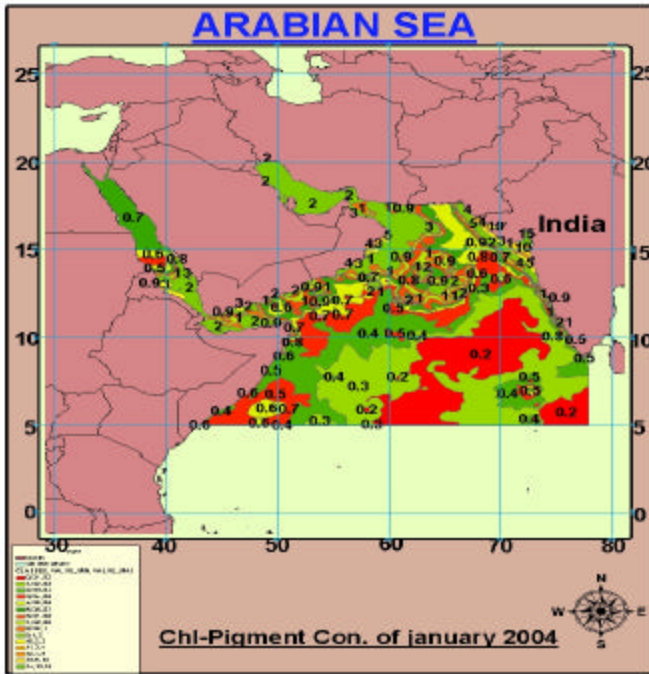
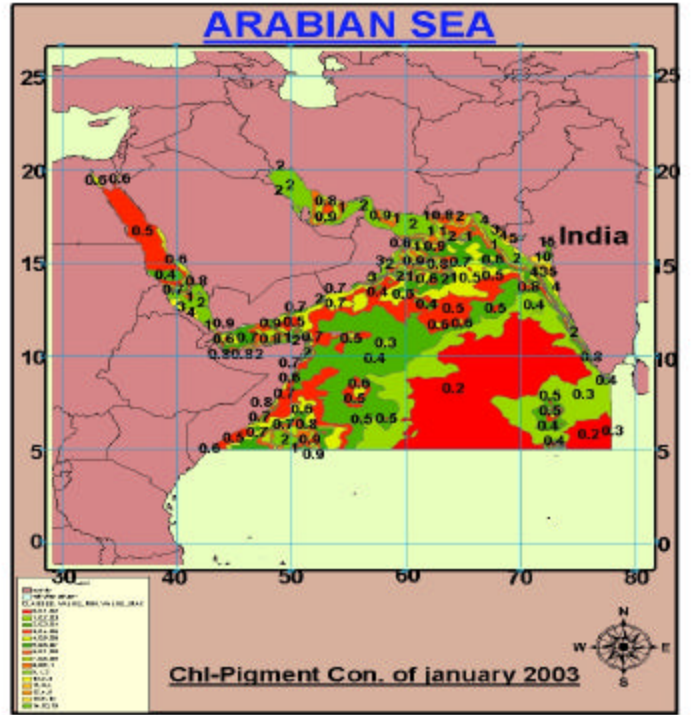
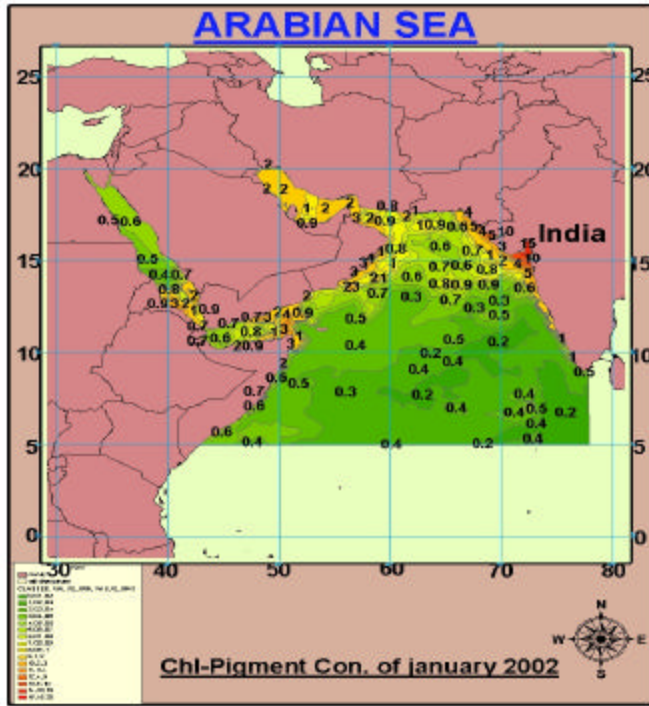


Fig-11. Inter-annual cycle of Chlorophyll pigment

Sea Surface Height

The sea surface height (SSH) anomaly in January is positive along the coastal boundary indicating a northward current along the west coast of India and southward current along the coast of Arabia and Somalia (Fig. 12). In the open ocean region the SSH anomaly was negative. But we also notice a positive SSH anomaly extending from southern part of the west coast of India, which is linked, to Rossby wave propagation. The sea surface height (SSH) anomaly distribution pattern in January 2003 is similar to that of 2002, except the magnitude, which was much less. In January 2004, the SSH anomaly once again was similar to 2002 both in pattern as well as in magnitude, but the path of +20 cm anomaly from west coast of India extended much towards the west, indicating the intense propagation of Rossby waves. In January 2005 the SSH anomaly pattern was much different and showed negative anomaly in most part of the Arabian Sea. The positive anomaly near the southern part of the west coast of India becomes much broader.

In summary, the SSH pattern during 2002 to 2004 was similar in distribution, though the magnitudes were different. But in 2005, the SSH anomaly was negative in most part of the Arabian Sea.

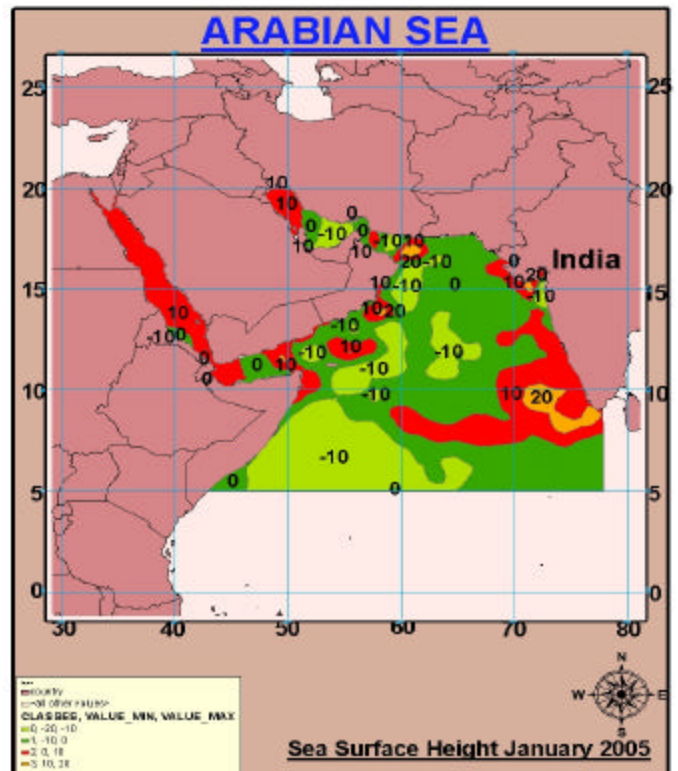
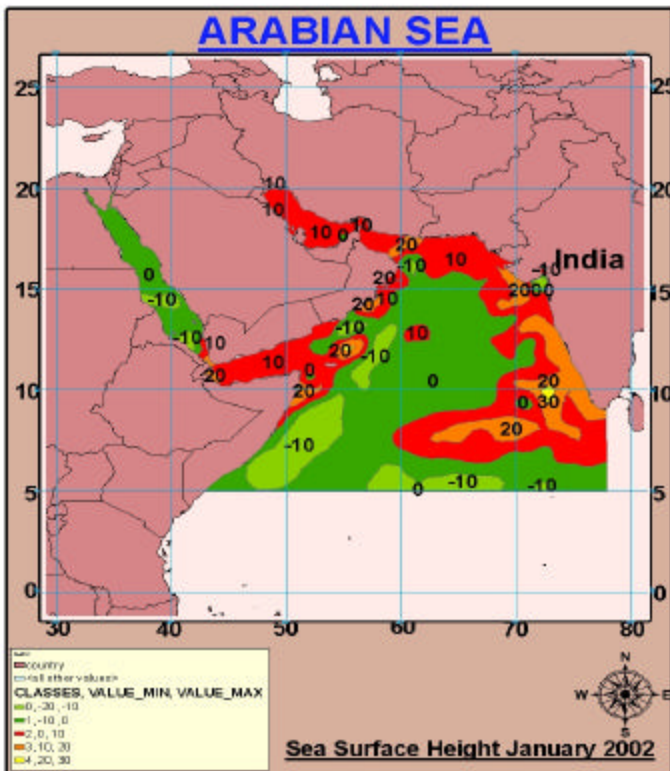
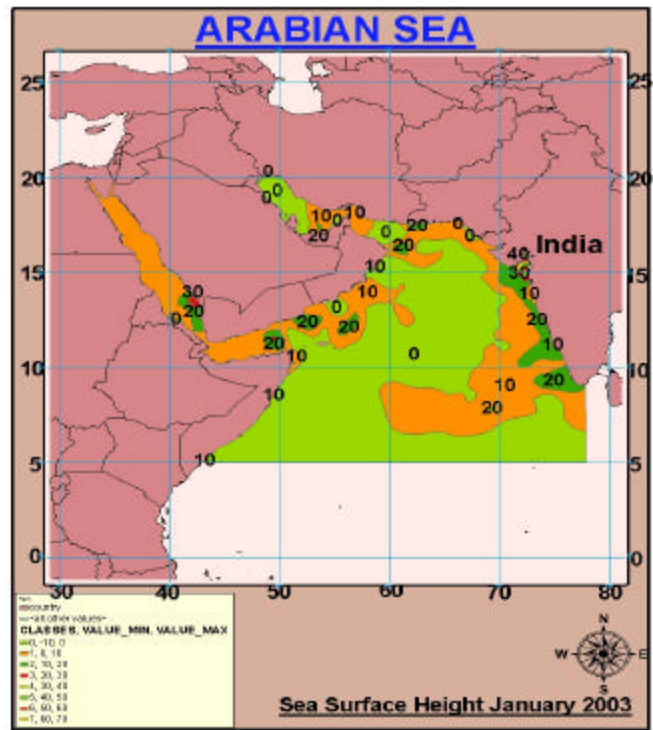
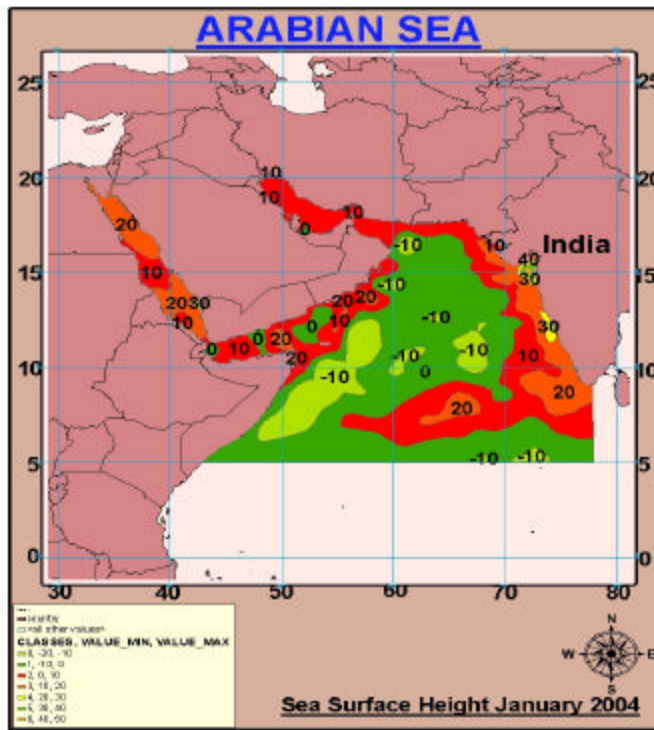


Fig-12. Inter-annual cycle of Sea Surface Height

August 2002-2005

Sea Surface Temperature

The SST distribution in August 2002 showed warmest temperature in the southeastern region and showed a progressive decrease towards the western boundary. Western boundary along Somalia and Arabia showed cold SST of 26°C. A small patch of 26°C was also noticed along the southern part of the west coast of India. This was the indication of upwelled water, which is cold. In August 2003, the coldest waters were found near the western boundary, which was 25°C. This was 1°C colder than that seen in August 2002 indicating that upwelling process must be intense in 2003. In August 2004 the SST was 24°C near the western boundary and this indicated that upwelling in this year must be more intense than the previous two years. In August 2005, coldest SST of 25°C was seen near the western boundary, while in the southeastern Arabian Sea SST reduce by 1°C from previous years value of 30°C to 29°C.

In summary, the coldest SST along the western boundary occurred in August 2004 while the warmest SST was seen in August 2002.

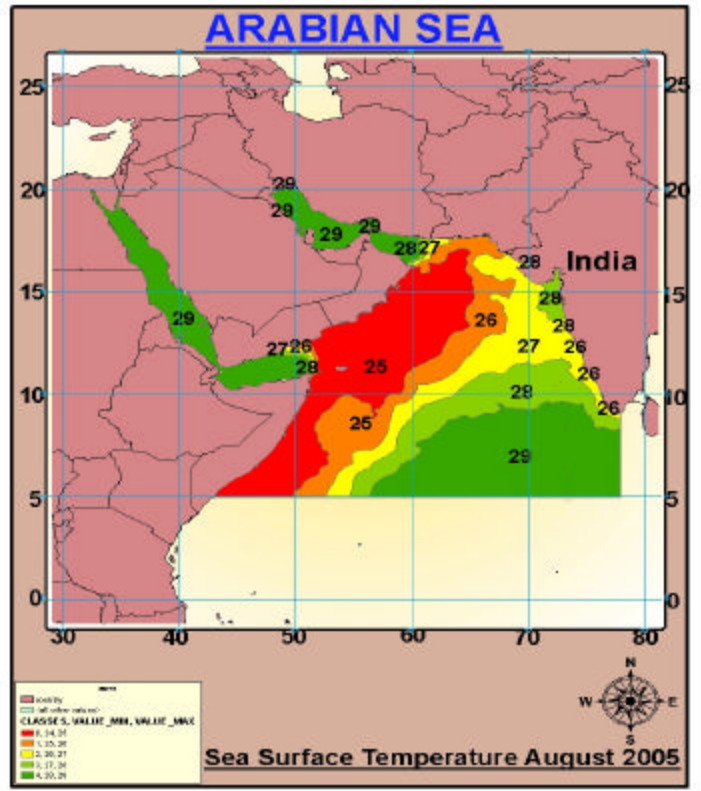
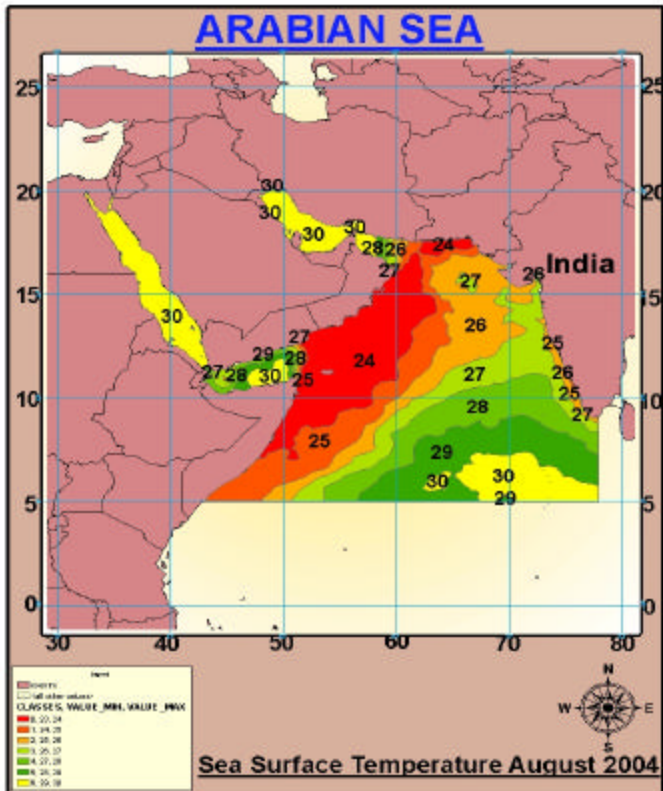
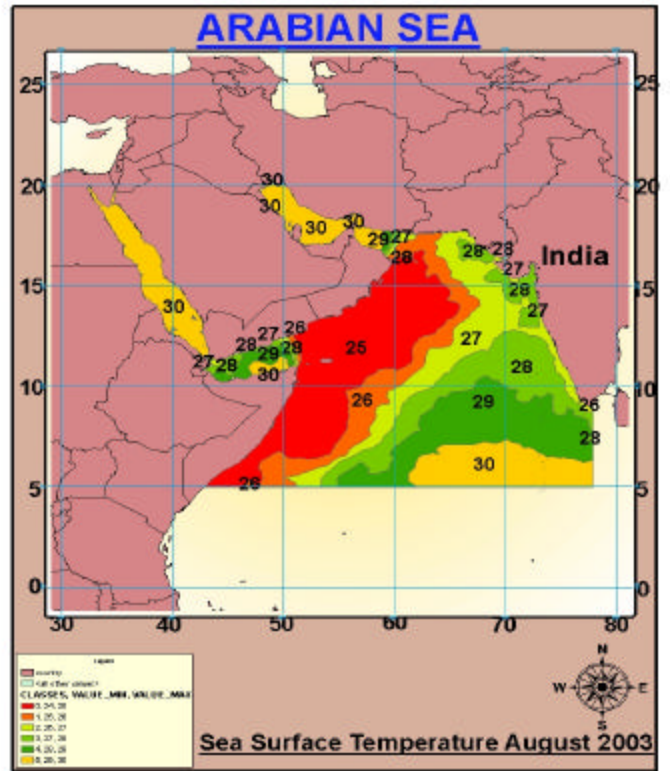
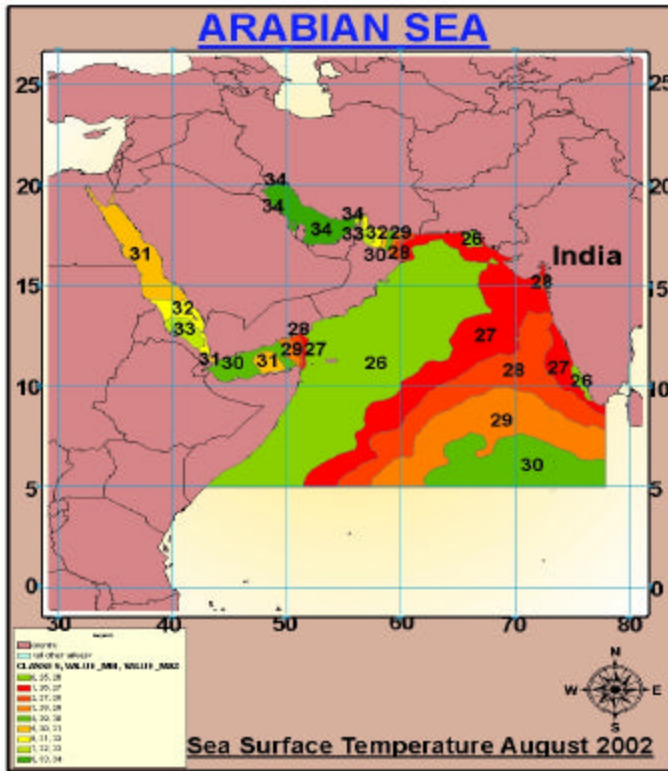


Fig-13. Inter-annual cycle of Sea Surface Temperature

In August 2002, chlorophyll pigment concentrations varied between 3 to 15 mg/m³ in both Arabian upwelling region as well as along the southwest coast of India. In the Somalia upwelling region it was 0.5 to 4 mg/m³. Except in a small region in the southeastern Arabian Sea, the chlorophyll pigment concentrations were in excess of 0.5 mg/m³. In August 2003, the chlorophyll distribution pattern was similar to that of 2002, but along the west coast of India it varied largely from 1 to 10 mg/m³, along Somalia it varied from 0.9 to 4 mg/m³, while in the Arabian upwelling region it was same as that of the previous year. In August 2004, the chlorophyll in the upwelling region of southwest coast of India was the highest varying between 0.7 to 10 mg/m³. Along the Arabian upwelling it varied from 4 to 15 mg/m³, while along the Somalia region, very near the coast it was between 4 and 5 mg/m³ but in the offshore region the variation was from 0.5 to 1 mg/m³. In August 2005, the chlorophyll concentration in general showed a decrease, but along the southwest coast of Indian concentrations were comparatively higher.

In summary, the chlorophyll pigment concentrations were highest during August 2005, while the least was noticed in August 2004.

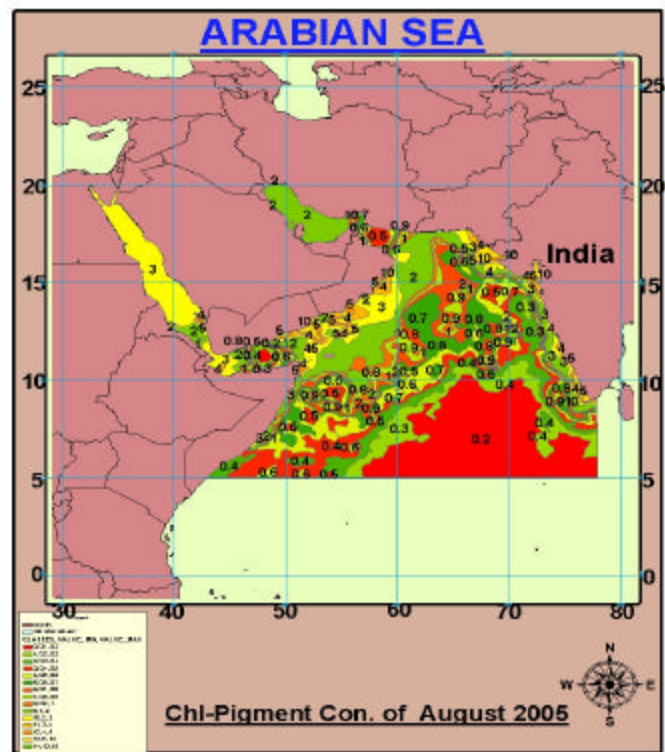
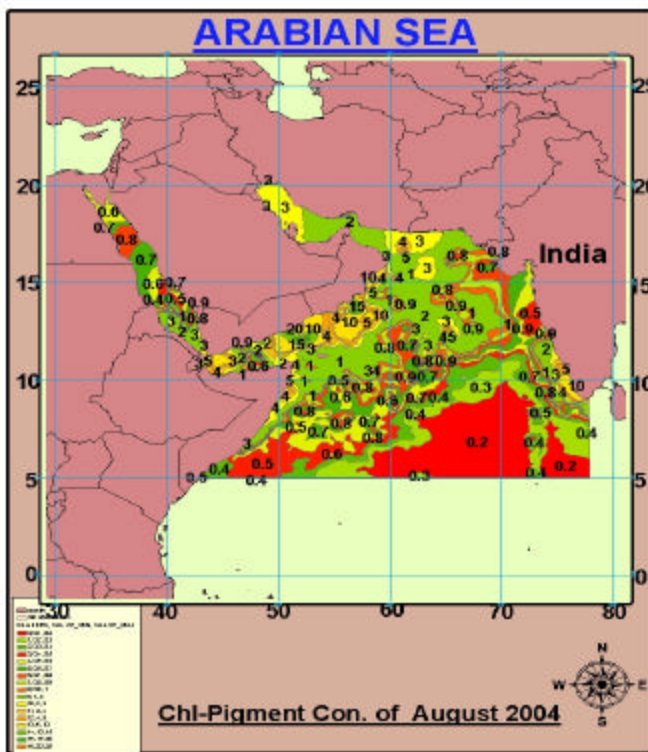
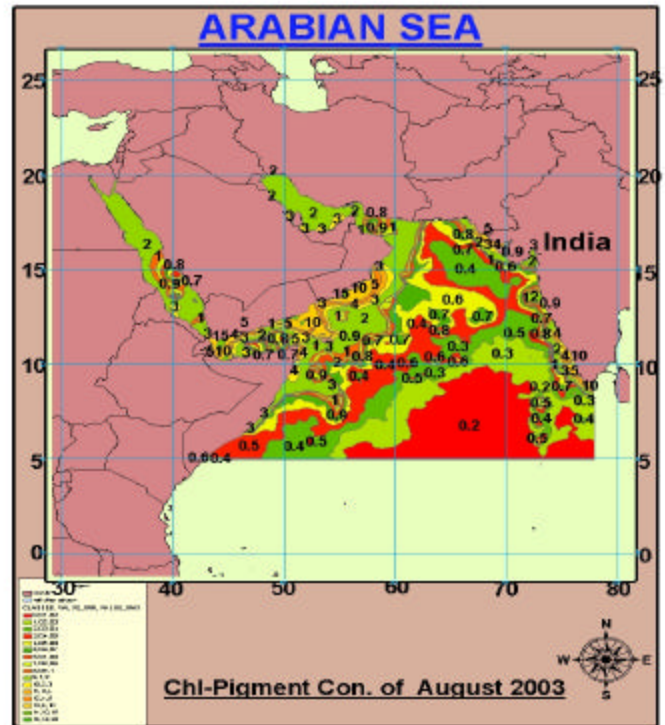
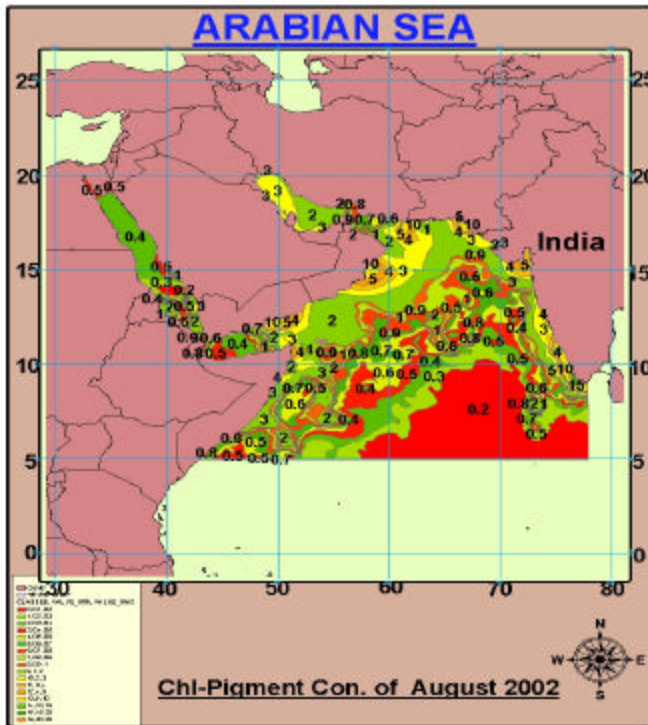


Fig-14. Inter-annual cycle of Chlorophyll pigment concentration

Sea Surface Height anomaly

In August 2002, the sea surface height anomaly was negative along both eastern and western boundaries of the Arabian Sea, which was 10cm along the west coast of India and between 10 and 20cm along the coasts of Somalia and Arabia. In the rest of the Arabian Sea SSH anomaly was positive. The westward extension of negative SSH anomaly from the southern part of the west coast of India indicated propagation of upwelling Rossby wave. In August 2003, though the SSH distribution pattern remained more or less similar to that of August 2002, the extent of positive SSH anomaly was considerably reduced. In August 2004, the distribution pattern of SSH anomaly was more similar to that of August 2002. But the westward extension of negative SSH anomaly from the southern part of the west coast of India was much less. Again in August 2005, the pattern of distribution of SSH anomaly was similar to that of 2004 and 2002. The noticeable difference was the region of positive SSH anomaly off Somali region resembling the shape of an eddy with a value of 40cm.

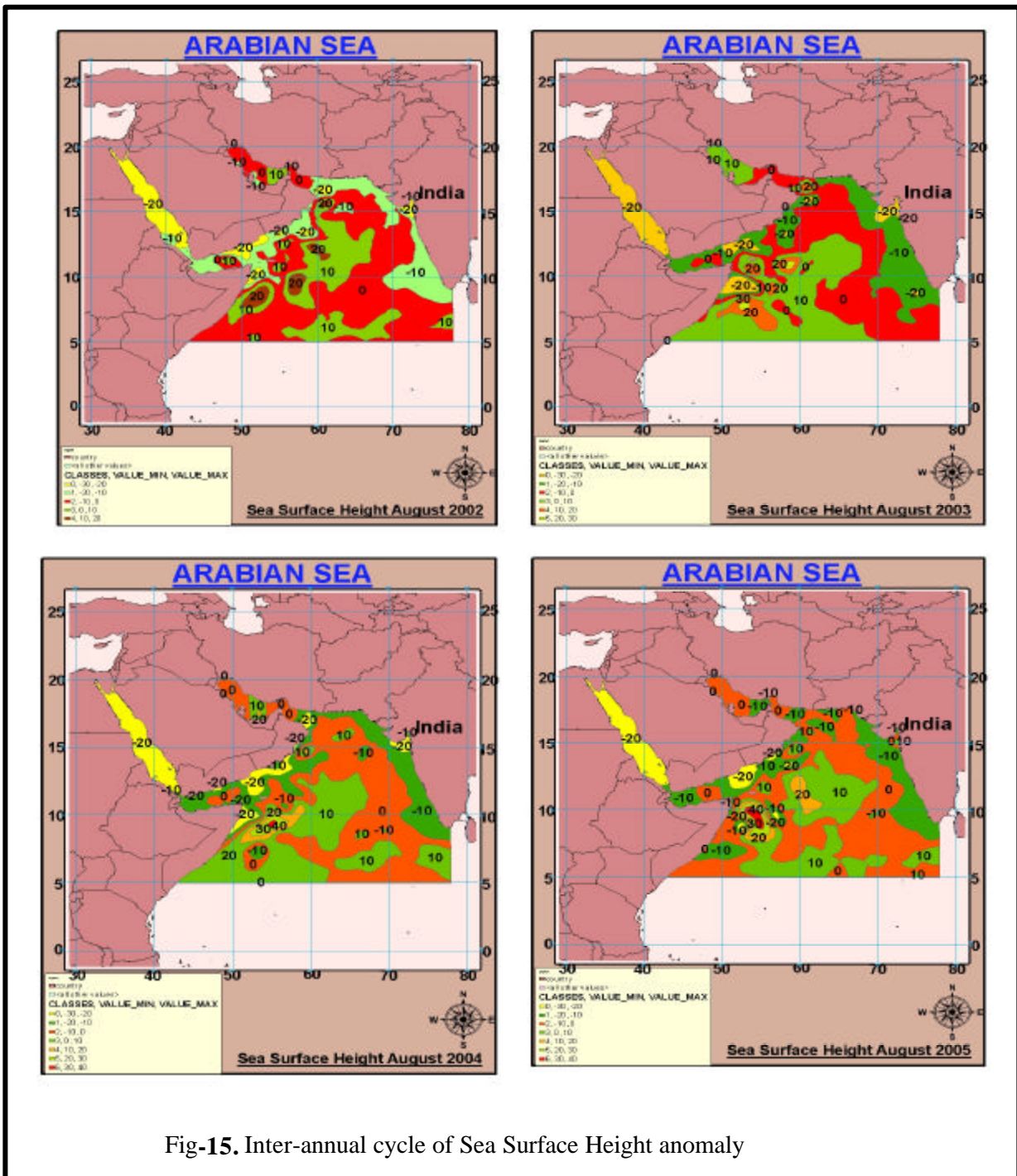


Fig-15. Inter-annual cycle of Sea Surface Height anomaly

Summary and Conclusion

The Arabian Sea, situated in the western part of the northern Indian Ocean is a tropical basin. It is bounded on the east by the Indian peninsula, on the north by Baluchistan and Sindh provinces of Pakistan and on the west by the landmass of Arabia and Africa. The environmental factors that influence this tropical basin are the seasonally changing winds from the northeast during winter (November-February) and southwest during summer (June to September). Accordingly, the waters of the basin will experience seasonal variations. The present study aims at understanding the seasonal and inter-annual variation of the Arabian Sea using satellite derived data with the help of GIS technique.

The spatial domain selected for the present study is 40°E and 78°E longitude and equator to 30° N. The remote sensing data with respect to sea surface temperature (SST), sea surface wind, sea surface height (SSH), and chlorophyll pigment concentration during January 2002 to December 2005 were used to understand the spatio-temporal variability of the Arabian Sea. The monthly mean SST data was obtained from Modis aqua, winds from Quikscat and chlorophyll pigment concentration from SeaWiFS. The SSH anomaly data was obtained from the merged product - Topex/Poseidon ERS 1/2 satellite which is 7-day snapshot. The spatial resolution of these data is 0.3° latitude x 0.3° longitude.

Geographical information system (GIS) was used for processing and analyzing the above parameters to determine the variability and detection of oceanic processes that are responsible for such variability.

The study showed a very strong inverse relation between SST and chlorophyll concentrations. Arabian Sea undergoes seasonal cooling during summer due to upwelling and advection, and in winter due to surface cooling under reduced solar heating. Upwelling along the coasts of Somalia, Arabia, and the west coast of India brings cold

and nutrient rich sub-surface waters to the surface, which supports the observed high chlorophyll concentrations. During winter the convective mixing in the northern Arabian

Sea supports high chlorophyll pigment concentrations. Due to strong solar heating, SST was warmest in spring (April), which supported least chlorophyll concentration.

The SST, chlorophyll pigment concentrations and sea surface height showed large inter-annual variability during the study period 2002 to 2005 during both winter (January) and summer (August). Of the four years analyzed, the winter was coldest in 2002 and warmest in 2003. In summer, the coldest temperature along the western boundary occurred in 2004 while the warmest was in 2002. However, the occurrence of chlorophyll pigment concentrations did not exactly follow the variations in SST pattern. The occurrence of negative SSH anomaly along the eastern and western boundary showed some variation from one year to the other. The extent to which the negative SSH moved westward is an indication of Rossby wave propagation, which also showed some inter-annual variability.

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