Panel Two: Airborne/Satellite Measurements of Water Quality

Panel Two addressed a number of applications of airborne and satellite remote sensing of estuarine and coastal waters. These approaches are generating data of interest to the scientific and management communities.

Airborne Remote Sensing (CBRSP)

Larry Harding's group has conducted airborne remote sensing of ocean color on Chesapeake Bay since 1989 as part of the Chesapeake Bay Remote Sensing Program (CBRSP) (Figures 16A-C). The initial motivation of this work was to quantify the high spatial and temporal variability of phytoplankton biomass as *chl-a* in the main stem of Chesapeake Bay, driven primarily by variability of freshwater flow from the Susquehanna River. CBRSP uses low-altitude surveys with light aircraft equipped with visible radiometers to measure the spectral quality and quantity of light reflected from the water. These data are used in conjunction with *in-situ* data on optical properties to estimate the Bay-wide distribution of *chl-a* on 20-30 flights per year, totaling over >340 flights to date. The technology used for these measurements has evolved from a three-waveband instrument designed to recover *chl-a* remotely, NASA's Ocean Data Acquisition System (ODAS), through two subsequent generations of instruments manufactured by Satlantic, Inc. of Halifax, Nova Scotia, the SeaWiFS Aircraft Simulator (SAS II, III). The instrument currently being used for Bay flights, SAS III, collects data at 13 wavebands including some specific additions to match capabilities of NASA's satellite instruments, the Moderate Resolution Imaging Spectrometers (MODIS), in the red region of the visible spectrum. CBRSP outputs include interpolated "maps" of *chl-a* and SST from >350 flights. The data are deposited at the NOAA Chesapeake Bay Program Office and eventually will be used to guide criteria attainment, now that specific regional and seasonal targets have been set for *chl-a*. Examples of *chl-a* maps for a sequence of six flights (6 March - 20 June 2000) reveal spatial and temporal variability regularly retrieved using aircraft remote sensing (Figures 17A-C).

The application of remotely-sensed data and information to management needs of Chesapeake Bay centers on the goal of reducing nutrient loading to the estuary, particularly nitrogen (N) as this macronutrient impacts phytoplankton biomass on a Bay-wide scale. Maps that show spatial and temporal variability of *chl-a* in years of contrasting precipitation and freshwater flow can help resolve changes of *chl-a* that are expected to accompany reductions of nutrient loads in the future.

The spring bloom is the most prominent feature of the annual phytoplankton cycle in the Bay. Phytoplankton develop high biomass in spring while incorporating nutrients into particulate organic matter, serving to fuel the Bay's food web and to promote deleterious effects of enrichment, such as low DO. Both scientists and managers recognize that increased nutrient loading to the Bay has acted to "fertilize" the lower estuary, alleviating N limitation and supporting increased phytoplankton biomass. The effect on the ecosystem appears increased *chl-a* in the polyhaline regions, particularly from the 1950s to the 1980s. Since 1989 when CBRSP began, there has been strong interannual variability of *chl-a* in the polyhaline areas coupled to freshwater flow. Low-flow years are characterized by reduced spring biomass, evident in *chl-a* images from aircraft remote sensing, whereas high-flow years typically have high biomass in the mesohaline to polyhaline regions. The complete time-series of *chl-a* data from aircraft remote sensing has been combined with models of primary productivity (PP) developed by Harding's group. From these data, monthly "climatologies" of *chl-a*, euphotic-layer *chl-a*, and PP for 1989-2001 have been developed, supporting predictive models for these ecosystem properties. The strengths of this approach are the high spatial and temporal resolution attained in the time series, careful calibration of instruments, generation of algorithms and models, and independent validation using data from a variety of sources, among them the CBP monitoring and LMER TIES programs.

Satellite Remote Sensing

Satellite-based remote sensing has many applications in estuarine and coastal waters. Janet Campbell of OPAL-UNH presented a brief history of ocean color remote sensing (Table 1). This approach originated with the launch of the Coastal Zone Color Scanner (CZCS) aboard the Nimbus-7 satellite in 1978. CZCS was operational for eight years with products consisting of surface maps of "pigment" concentrations including both *chl-a* and degradation compounds (phaeopigments) not distinguished from active *chl-a*. CZCS was a proof-of-concept mission that gave extensive coverage of the oceans from scenes combined over relatively long (monthly, annual) time periods to produce a global view of pigment distributions. Following CZCS, there was a 10-year absence of satellite ocean color data until the Ocean Color and Temperature Sensor (OCTS) was launched in 1996. This short-lived mission provided data for less than a year before instrument failure. In August 1997, the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) was launched. SeaWiFS is owned and operated by a commercial company, Orb Image, and NASA has purchased the rights to the data and has provided them to the research and education communities at no cost. SeaWiFS nominally acquires complete global coverage every two days (http://seawifs.gsfc.nasa.gov), although cloud cover lessens this frequency. A combination of three SeaWiFS bands to simulate red, green, and blue light reflected from the ocean is used to create a "true color" image, as shown in an example for coastal waters near Cape Hatteras, North Carolina, illustrating the effects of Hurricane Floyd (September 1999) on turbidity (Figure 18). Bright blue corresponds to a predominance of "blue" water as one might see from a ship on the open ocean, whereas vegetation on land is green. Bright colors (yellow) correspond to high reflectance and indicate suspended matter mixed into the upper ocean as a result of the hurricane's passage.

Sensor	Satellite	Country	Dates	Spatial Resolution	No. of Bands	Comments
CZCS	Nimbus-7	USA	Nov 78 – Jul 86	825 m	5	Proof-of-concept
MOS	IRS P3	Germany/ India	Mar 96 –	523 m	13	Requires ground station
OCTS	ADEOS-1	Japan	Aug 96 – Jun 97	700 m	8	+ 4 thermal IR bands for SST
SeaWiFS	SeaStar	USA	Aug 97 –	1100 m	8	Commercial data, free to researchers
OCI	ROCSAT-1	Taiwan	Dec 98 –	800 m	6	Latitude coverage 35N-35S
OCM	OceanSat-1 (IRS P4)	India	May 99 –	360 m	8	+ Scanning microwave - SST
MODIS	Terra	USA	Dec 99 –	1000 m	9	+ 27 other bands for land, atmos, SST
OSMI	KOMPSAT-1	S. Korea	Dec 99 –	850 m	6	Selectable bands

Table 1. Characteristics of ocean color sensors (past and present). Arrows indicate ready availability of data. Note there are now two MODIS instruments with the second on Aqua.

Despite the availability of rich sources of data, Campbell observed that managers seldom access them and often view the learning curve to develop expertise as a barrier. Consequently, most remain unfamiliar with products that can be obtained that don't require technical expertise in image processing or interpretation. Campbell specifically noted the availability of numerous products from the NASA Distributed Active Archive Center (http://daac.gsfc.nasa.gov) with potential applications for coastal managers. The DAAC represents an entry point for access to data and information from a growing set of ocean color sensors with increasing capabilities in coastal waters.

Satellite remote sensing offers the advantage of regular, synoptic coverage by instruments that generally take data for years once they are launched, distinguishing this approach from airborne remote sensing whose advantage is spatial resolution. In the past few years, NASA has supported extensive work using SeaWiFS in Chesapeake Bay, including optical sampling to support the analysis of regional SeaWiFS data (Figures 19A, B). SeaWiFS *chl-a* images have ~1 km resolution (same resolution as gridded and contoured aircraft products presented by Harding). For the main stem of Chesapeake Bay, this resolution is clearly appropriate to describe the major features of the annual phytoplankton cycle in the Bay, including the spring diatom bloom and summer outbreaks of dinoflagellates. Recent advances have allowed us to generate time series of *chl-a* for the period 1998-2003, based on the use of semi-analytical models tuned with local optical data that give accurate *chl-a* retrievals for the Bay.

New ocean color instruments are currently in orbit with greater capabilities than SeaWiFS. These include the Moderate Resolution Imaging Spectrometer (MODIS) launched on the Terra satellite platform in December 1999, and a second MODIS launched on the Aqua platform in April 2002 (http://modis. gsfc.nasa.gov). Both Terra and Aqua are part of NASA's Earth Observing System (EOS) that consists of large platforms carrying multiple sensors to measure a variety of environmental parameters. MODIS represents a state-of-the-art ocean sensor for earth imaging, as shown in SST and *chl-a* data for the Arabian Sea (Figures 20A, B). Terra and Aqua MODIS generate SST and *chl-a* products at 1 km for the global ocean, comparable to the spatial resolutions of the NOAA Advanced Very High Resolution Radiometer (AVHRR) for SST and SeaWiFS for *chl-a*. The 36 spectral bands of MODIS include several with higher spatial resolution, with five bands at 500 m and two bands at 250 meters. MODIS generates a large number of ocean products, including four measurements of SST, and five estimates of PP for the terrestrial and ocean biosphere. (Since the workshop, the product suite of MODIS has been edited to include fewer standard products.) In addition to ocean products used to retrieve *chl-a* and PP, MODIS provides a *chl-a* fluorescence product that relies on solar-stimulated fluorescence in the red region of the visible spectrum. The ratio of *chl-a* fluorescence to *chl-a* concentration is a measure of "fluorescence efficiency," believed to give information on the photosynthetic potential of phytoplankton. A sequence of sensors, from SeaWiFS to MODIS, and eventually to new missions such as the National Polar-orbiting Operational Environmental Satellite System (NPOESS), will generate *chl-a* for two decades, providing coverage required for resolving long-term trends from variability.

The higher-resolution bands of MODIS can be combined to produce composite images that have potential application to Chesapeake Bay. Qualitative information on SPM contained in such images can be used to track water movements and define the spatial extent of riverine influence. Campbell presented recent work to develop an index of fluvial influence (IFI) based on this approach. Elevated SPM in water from the Mississippi produces an increase of water-leaving radiance at 550 nm (L_w 550) that can be used to show movement of the freshwater plume (Figure 21). Campbell suggested the IFI has direct applicability for tracking water movements in the Bay and in adjacent waters of the middle Atlantic bight.

Satellite sensors provide data on a number of optical properties that can be used to estimate important ecosystem attributes. For example, time series of *chl-a*, K, SST, and PP can already be obtained from several current satellite instruments, and other instruments are scheduled for launch in the coming decade. Calibration and validation are essential to recover accurate information from satellite sensors, and to this end, the combination of remote sensing with *in-situ* optical measurements is critical. The need for comparable data from different sensors led to the NASA project, the Sensor Inter-comparison and Merger for Biological and Interdisciplinary Oceanic Studies (SIMBIOS). SIMBIOS has supported a range of data collection and analysis activities, including optical sampling in diverse waters of the world's oceans, to calibrate and validate algorithms, and to compare properties retrieved from instruments with different capabilities.

NASA is funding a new program directed at applications to promote "partnering" with prospective users of data and information developed by the scientific community. There are uses for data and information from satellites other than the original scientific purposes, especially as components of education and outreach efforts. Campbell described a project in Maine entitled "Gaia Crossroads" that uses satellite imagery in K-12 classrooms to stimulate interest in the environment and promote the use of earth system imagery to engage students in science curricula.

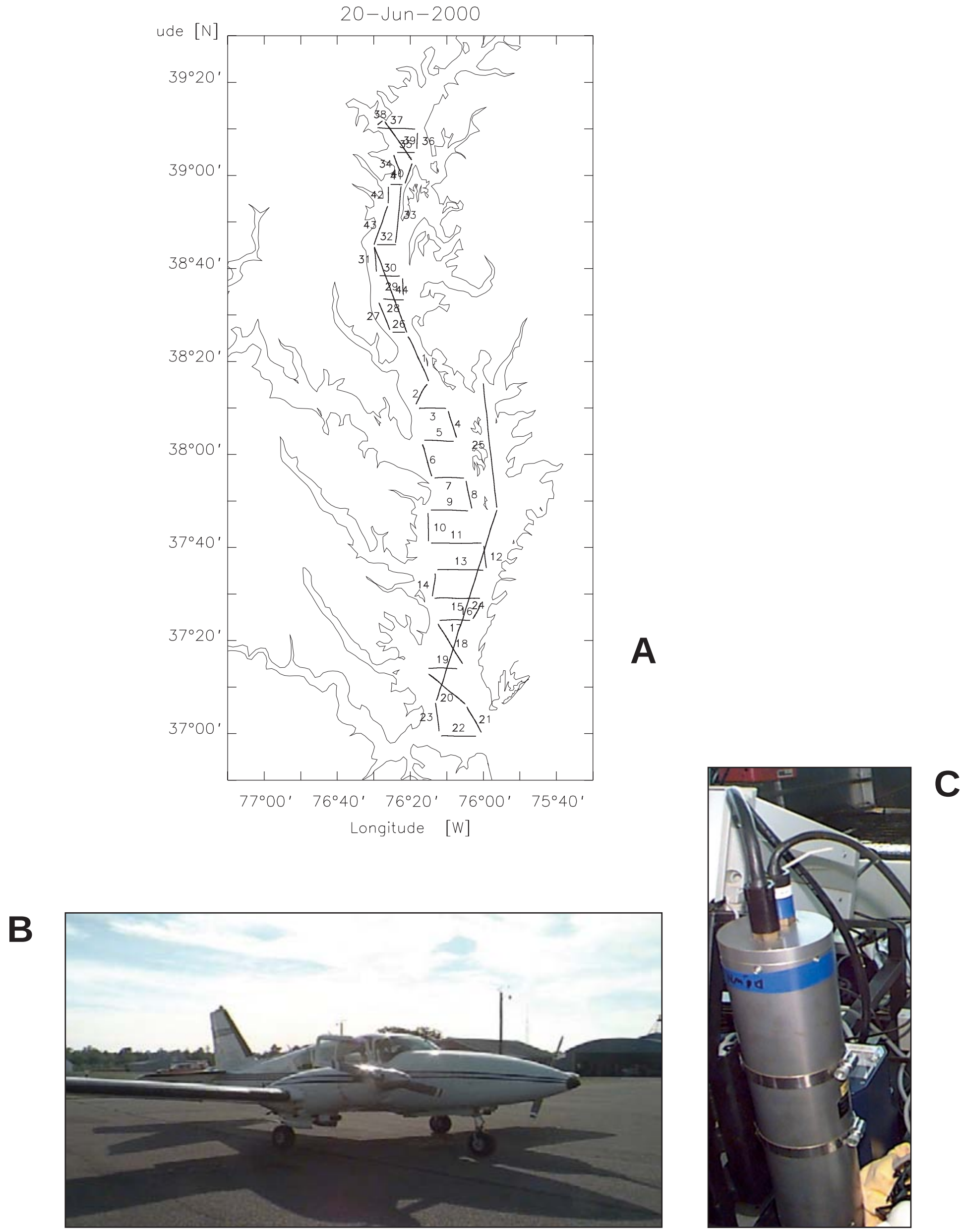

Figure 16. (A) Flight tracks for aircraft remote sensing of ocean color in Chesapeake Bay. (B) Piper Aztec currently used for main stem Bay flights. (C) SAS III radiance sensor mounted in the aircraft.

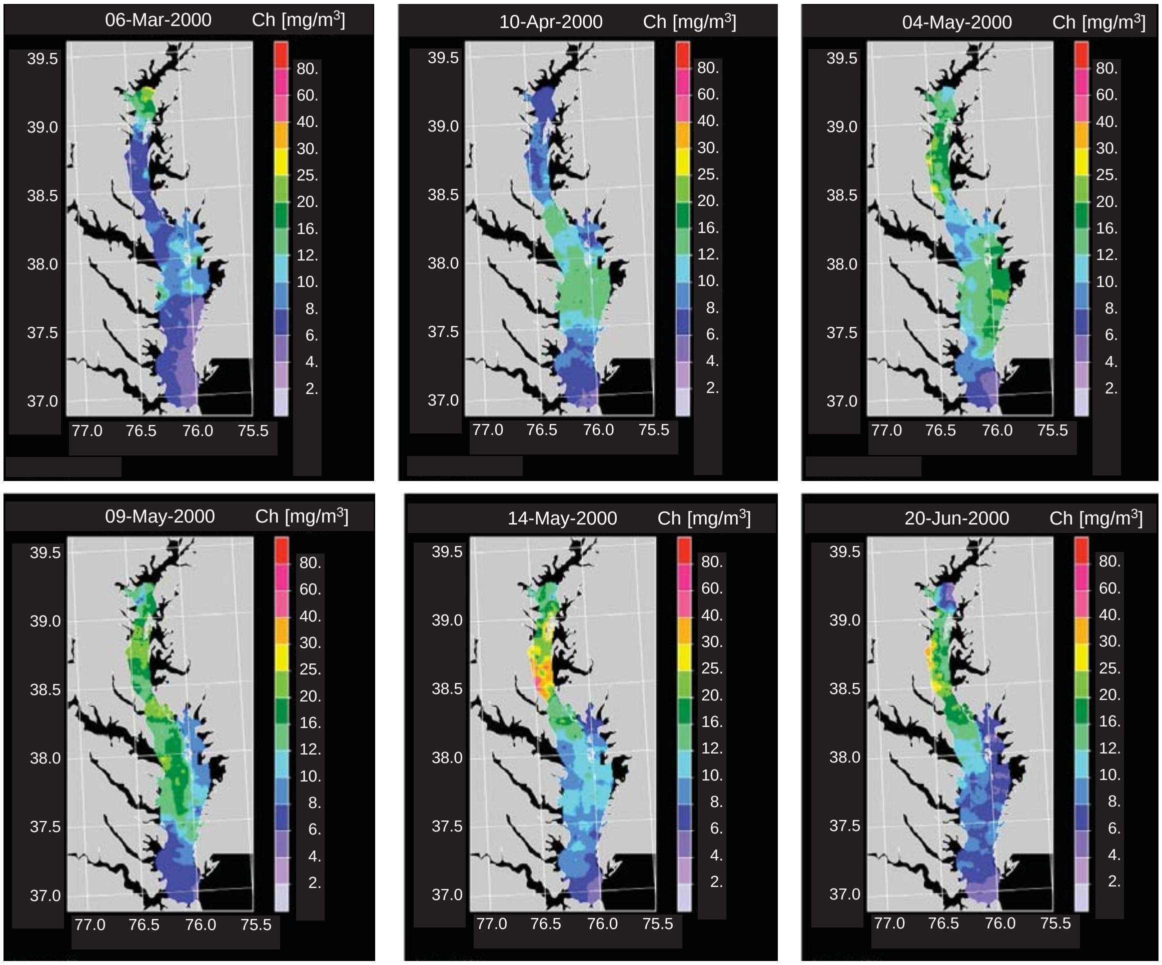

Figure 17. Chl–a *concentrations in the main stem of Chesapeake Bay from aircraft remote sensing of ocean color using the SeaWiFS Aircraft Simulator (SAS III) for six flights in spring 2000.*

Figure 18. True color image from the Sea-viewing Wide Field-of-View Sensor (SeaWiFS) of the Middle Atlantic, showing the effects of Hurricane Floyd adjacent to Albemarle-Pamlico Sound, North Carolina.

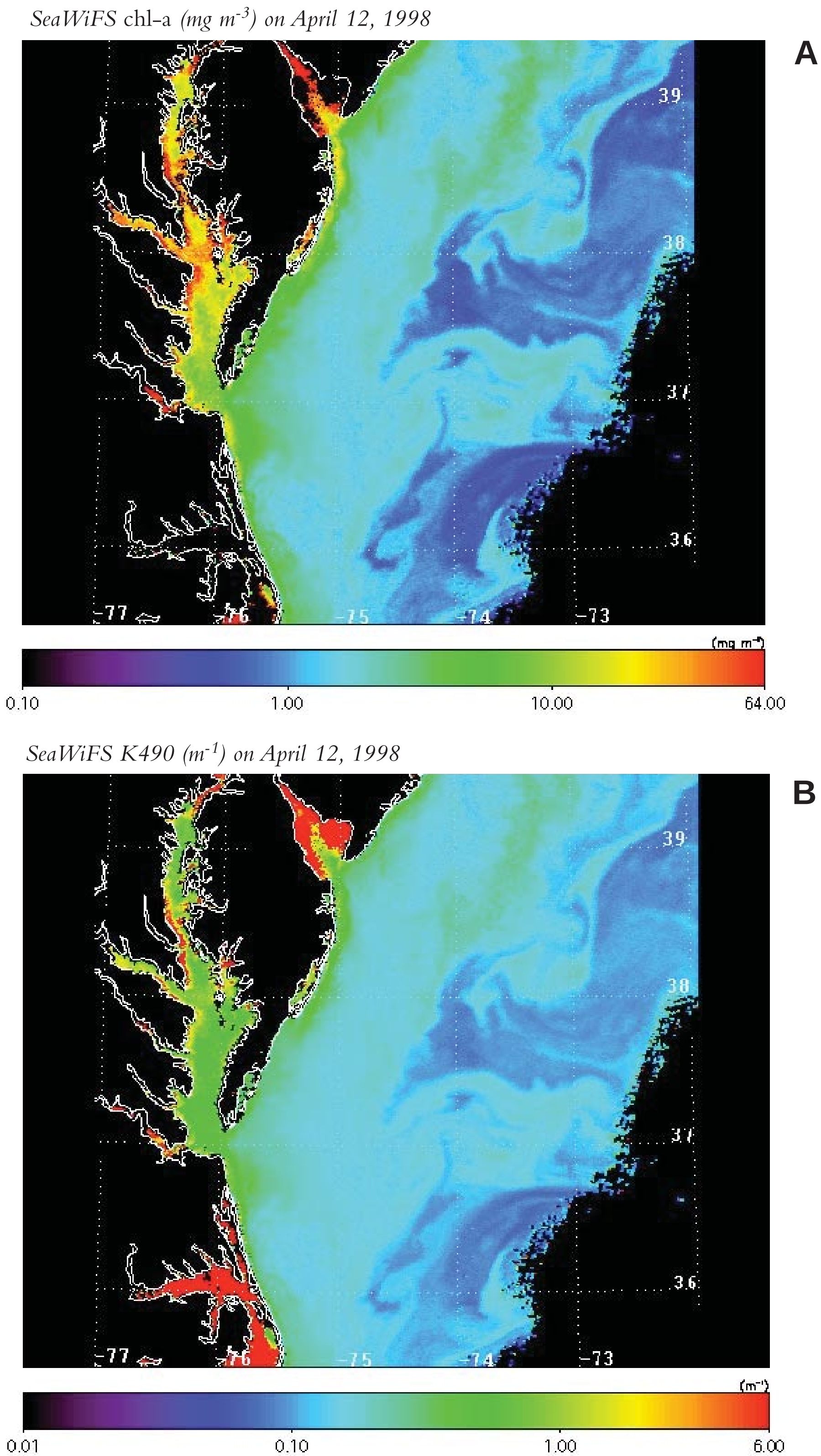

Figure 19. (A) SeaWiFS chl-a *and (B) K490 images for the middle Atlantic Bight including Chesapeake Bay.*

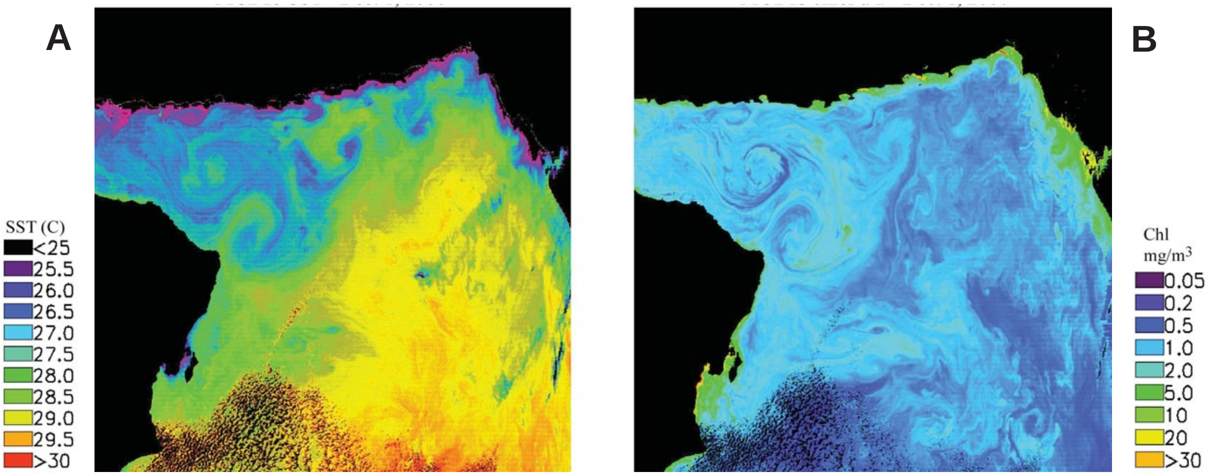

Figure 20. MODIS data for the Arabian Sea, 1 December 2000 (A) SST and (B) chl-a.

Figure 21. Index of fluvial influence (IFI) for the Mississippi R. plume (Salisbury et al., 2000).