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EARTH SYSTEM MONITOR

A guide to NOAA's data and information services

Optical remote sensing of the coastal ocean

Future directions for observing and monitoring

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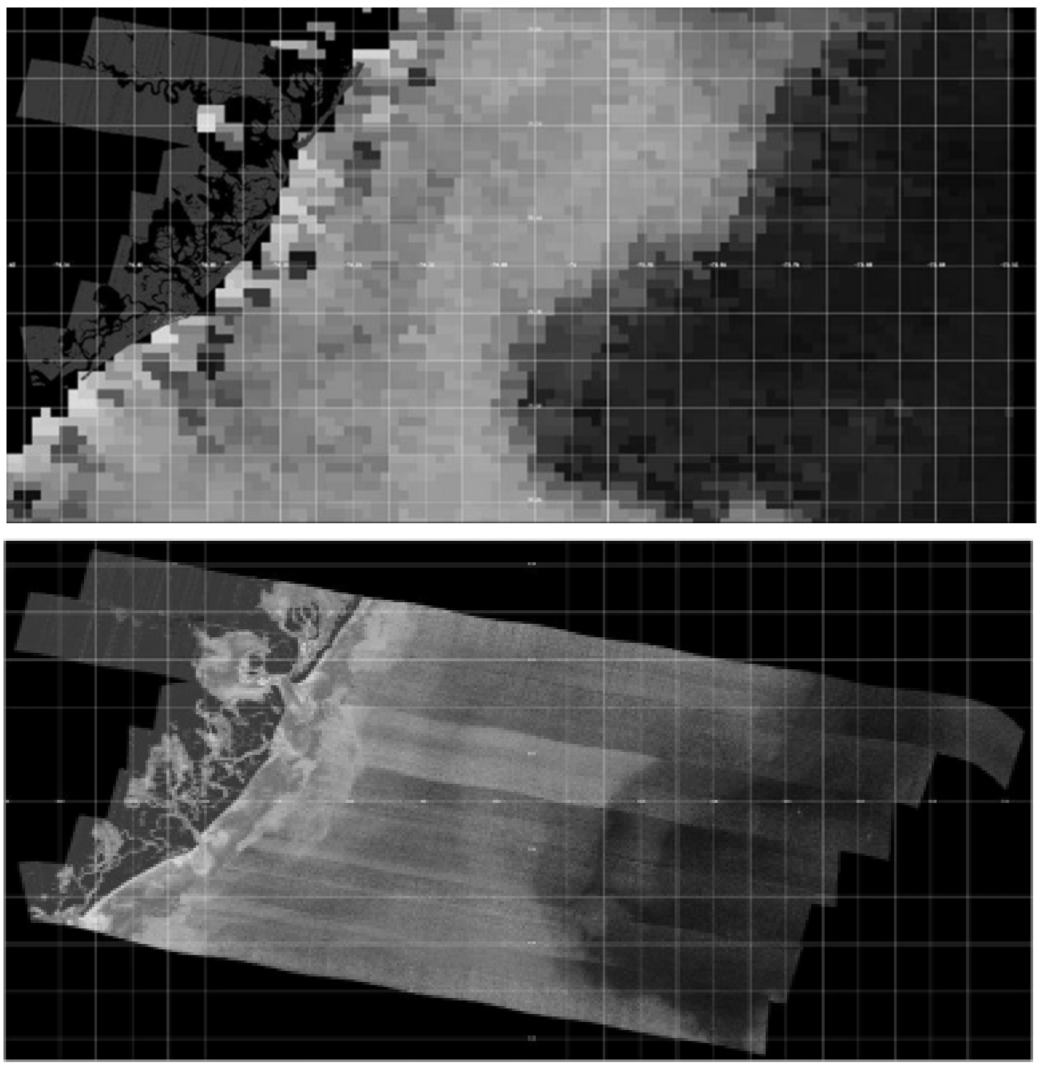
The coastal ocean is the most productive and impacted part of the global ocean. Over 60% of the worlds population lives near the coast. Agriculture, mining, land clearing, dams, urban development and other activities all affect the coastal ocean through changing patterns in runoff and river discharge. Important uses of the coastal ocean,

— continued on page 2



▲ **Figures 1a,b.** Comparison of SeaWIFS 1 km GSD (top) and airborne PHILLS 8 m GSD data (bottom). For scale each white box is approximately 4 km wide and 5 km high. There are two fronts visible in this image of suspended sediments, one offshore and the second nearshore about 3 km off the barrier islands. Both sensors pick up these features, but there is much more detail in the PHILLS 2 data due to the higher spatial resolution. In particular, in the nearshore frontal region there are multiple fronts and features that are visible in the PHILLS data that are not resolved in the SeaWIFS data. Inshore of the barrier island the SeaWIFS resolution is not adequate to image the bays and estuaries. The PHILLS data shows estuarine water properties and bottom features in these complex regions.

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Optical remote sensing, *from page 1*

such as oil and gas production, shipping, and waste water disposal can have significant effects on ecosystem health. At the same time, the coastal ocean is the source for 90% of the worlds fisheries and a growing mariculture industry. Additionally, there is extensive recreational use of the coastal ocean for fishing, water sports, sightseeing and boating. These uses depend on a healthy coastal ecosystem to support productive fisheries and mariculture as well as the aesthetic value and ecological function of salt marshes, coral reefs, kelp forests, and other ecosystems. These uses highlight the importance of the coastal ocean and the need for monitoring the health of the ecosystems within it.

Satellite remote sensing systems should be an excellent tool for monitoring the coastal ocean. Optical satellite remote sensing systems have proven extremely valuable for monitoring the health and productivity of the open ocean and land areas. However, to date these systems have had limited utility for the coastal ocean. To better understand this, we consider several reasons why the current systems are not particularly useful for coastal ocean waters. We review the types of remote sensing applications that would be useful in the coastal ocean and examine the capabilities of the current systems and their ability to meet these needs. Finally, we suggest remote sensing systems that are specifically designed to observe the coastal ocean that would greatly improve our ability to monitor this important region.

Coastal ocean remote sensing applications

Current ocean color remote sensing instruments are designed for the open ocean where microscopic plants, called phytoplankton, are the primary optically active material in the water and other constituents vary proportionately with their concentration. These sensors have eight or so narrow spectral bands for performing atmospheric correction and measuring and deriving the ocean properties, and yield imagery with 1 – 4 kilometer spatial resolution (IOCCG , 1998). These systems work well for imaging the open ocean and continental shelf, however,yet are inadequate to fully image the much more complex coastal ocean. There are several reasons for this. First, the coastal ocean contains a wider range of water column properties, such as suspended sediments and shallow bottom reflectance, and requires additional spectral channels for accurate retrieval. Second, the process of atmospherically correcting ocean color imagery, which removes 90 – 95% of the signal received at the sensor, is much more difficult in the coastal regime. The spectral bands and assumptions employed over the open ocean are frequently insufficient and invalid for performing atmospheric correction over coastal waters. For example, the near infrared channels normally used for atmospheric correction over the open ocean have negligible water-leaving radiance such that any signal may be assumed to be solely from the atmosphere or sea surface. Over coastal waters, these wavelengths receive significant water-leaving signals resulting from shallow or sediment laden reflectance that can escape the surface waters. Therefore, additional channels at longer wavelengths where light is more strongly absorbed by the water must be added for accurate atmospheric correction. Third, increased dynamic range is required so that the sensor does not saturate when imaging the beach or other bright objects that are typical of a coastal scene. Fourth, coastal features are more complex spatially than the open ocean resulting from the interactions of tides, currents, and fresh waters flows, and higher spatial resolution is required. Finally, the coastal ocean can be extremely dynamic and some applications may require daily to hourly sampling.

Because of the diversity of applications in the coastal ocean no single sensor system will meet all of the requirements. Each application has unique requirements for spatial resolu-

— continued on page 4

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Seventh International Conference on Coelenterate Biology (ICCB)

Information, registration, and abstract submission are now available for the Seventh International Conference on Coelenterate Biology (ICCB) at *www.nhm.ukans.edu/inverts/iccb/.*

ICCB7 will occur 6-11 July 2003 at the University of Kansas, Lawrence. This will be the first ICCB to be held in the US, and one session (or more) will be the 2003 North American meeting of the International Society for Reef Studies.

Themes of the meeting are "biogeography and environmental biology of coelenterates" (anticipated sessions include those on freshwater biology, bioinformatics, coral reefs, and deep-sea ecology), "evolutionary and developmental biology of coelenterates" (anticipated sessions include those on taxonomy and systematics, reproduction and development, and life cycles), and "coelenterate anatomy, physiology, and behavior" (anticipated sessions include those on neurobiology, cnidae, and gametogenesis). Integration of presentations is an overarching goal of the meeting.

Workshops will follow the ICCB for 1-2 days, depending on topic and number of participants. Those being planned include "electronic sources of information about anthozoans," and "octocorallian systematics."

Graduate student members of ISRS who are citizens of a developing country and are enrolled in graduate study in a developing country are eligible to apply for a travel grant from ISRS and the ICCB7.

We hope to see you in Kansas in July!

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News briefs

Kilimanjaro ice cores provide new East African paleoclimate record

The National Oceanic and Atmospheric Administration' (NOAA) Paleoclimatology Program has archived new ice core data from Mount Kilimanjaro, whic which provides a paleoclimatic record for eastern equatorial Africa over the last 11,000 years. Published by Thompson *et al.* in *Science,* October 18, 2002, the record indicates three periods of abrupt climate change: ~8.3, ~5.2, and ~4 thousand years ago. The latter is coincident with the "First Dark Age," the period of the greatest historically recorded drought in tropical Africa. The data and research summary can be obtained on thee NOAA Paleoclimatology Program website at: *http://www.ngdc.noaa.gov/paleo/pubs/thompson2002/thompson2002.html.*

Coastal GTOS meeting

David Clark and John Kineman of NGDC recently attended the first meeting of the Coastal Panel of the Global Terrestrial Observing System (GTOS), at East Carolina University in Greenville, North Carolina. The goal of the meeting, attended by experts from academia, both foreign and domestic, was to develop an initial set of variables for monitoring and assessing change in the coastal zone related to climate change and direct human influences.

Clark and Kineman presented an overview of coastal programs in NOAA and a discussion of issues in coastal ecosystem monitoring and assessment. A preliminary framework and initial recommendation of needed coastal terrestrial observations was developed by the panel and was related to the concept of an "integrated coastal ecosystem." Subgroups were formed that will continue to collaborate between meetings to finalize recommendations. The next meeting is planned for Spring 2003.

International Earth Observation Satellite Group

On November 21, 2002, Greg Withee, NOAA Assistant Administrator for Satellite and Information Services, assumed chairmanship of the Committee on Earth Observation Satellites (CEOS) at the conclusion of the 16th CEOS Plenary in Frascati, Italy. CEOS, the key coordination mechanism for space-based Earth observation, now comprises 23 space agencies and 21 associates (with UNESCO becoming an associate at the 16th Plenary). In assuming the CEOS Chairmanship, Greg Withee outllined an ambitious CEOS work plan for the upcoming year that in particular will capitalize on the need to utilize data from up to 100 new satellites in the next decade, transferring the benefits to society. Building upon past CEOS efforts, NOAA as CEOS Chair intends to strengthen the Integrated Global Observing Strategy Partnership (in which CEOS interacts with *in situ* observation providers); to emphasize satellite data utilization in connection with several international symposia; to lead CEOS efforts in follow-on activities to the Johannesburg World Summit on Sustainable Development; and to study the possibility of harmonization amoung CEOS and other space-related international coordination mechanisms.

New long-time series of ENSO appears in *Nature*

An article describing how ENSO (El Nino-Southern Oscillation) has varied over the past 12,000 years, co-authored by NOAA's Paleoclimatologist David Anderson, appeared in the November 15, 2002, issue of *Nature*. The lead author was Christopher Moy, formerly of the NOAA Paleoclimatology Program and te Cooperative Institute for Research in the Environmental Sciences and now at Stanford University. The article reveals how El Nino-related floods in the Ecuadrian mountains reached their present level 7000 years ago, and how El Nino has varied from one millenium to the next. The significance of the new long-time series lies in showing that El Nino is a non-stationary aspect of climate. The data will be distributed by the NOAA Paleoclimatology Program at: *http://www.ngdc.noaa.gov/paleo/pubs/moy2002/moy2002.html.*

Optical remote sensing, *from page 2*
tion, field of view, spectral bands, and sampling frequency (Table 1). In particular, spatial resolution requirements vary widely depending upon the application. For large shelf features 1 km resolution imaging is suitable.

Applications / Issues	**Spatial Resolution x Extent**	**Temporal Resolution**	**Examples of suitable platforms / sensors**
River plumes, outfalls	(20 m – 1 km) x (1 km – 100 km)	hours – weeks	COIS, SeaWiFS, MERIS, MODIS, Geostationary
Tidal plumes, jets, frontal dynamics	(20 m – 1 km) x (1 km – 10 km)	Hours	Airborne, Geostationary
Harmful algal blooms, aquaculture, coastal water quality	(100 m – 1 km) x (1 km – 100 km)	days – weeks	COIS, SeaWiFS, MODIS, Geostationary
Bathymetry and shallow benthic habitat: distribution, status	(1 m – 30 m) x (1 km – 100 km)	weeks to months	Airborne platforms, COIS, Landsat TM, Ikonos, SPOT
Maritime operations: navigation, visibility.	(20 m – 1 km) x (20 km – 100 km)	Hours to days	COIS, SeaWiFS, Geostationary
Oil spills.	(100 m – 1 km) x (1 km – 100 km)	Hours – days	Airborne, MODIS, COIS, Geostationary
Operational fisheries oceanography	(1 km) x (1000 km)	Days	SeaWiFS, MODIS, Geostationary
Tidal marshes	(1-30 m) x (1-20 km)	Weeks to months	Airborne, COIS Landsat TM, SPOT
Coastal geomorphology	(1-30 m) x (1-20 km)	Weeks to months	Airborne, COIS Landsat TM, SPOT

Table 1: Representative applications or issues that have been addressed using remote sensing data. Spatial resolution, area coverage and temporal resolution are key parameters to consider when selecting a sensor for each application. See Table 2 for a description of the sensors.

Satellite	Sensor	Swath	Pixel Size	type	Web Address
Aircraft	AVIRIS	2.6-11 km	5-20 m	HS	http:://aviris.jpl.nasa.gov
Aircraft	PHILLS	1-8 km	1-8 m	HS	http://rsd-www.nrl.navy.mil/7212
NOAA	AVHRR	~2000 km	1000 m	MS	http://perigee.ncdc.noaa.gov/docs/intro.htm
Landsat 7	ETM+	185 km	30 m	MS	http://landsat7.usgs.gov/
Landsat 7	Pan	185 km	15 m	Pan	http://landsat7.usgs.gov/
Ikonos	MS	5 km	4 m	MS	http://www.spaceimaging.com/
Ikonos	Pan	5 km	1 m	Pan	http://www.spaceimaging.com/
OrbView 2	SeaWiFS	~2000 km	1000 m	MS	http://seawifs.gsfc.nasa.gov/SEAWIFS.html
Terra	MODIS	~2000 km	1000 m	MS	http://modis.gsfc.nasa.gov/MODIS/
Aqua	MODIS	~2000 km	1000 m	MS	http://modis.gsfc.nasa.gov/MODIS/
ENVISAT-1	MERIS	1150 km	300 m	MS	http://envisat.esa.int/
COIS	COIS	20 km	20 m	HS	http://rsd-www.nrl.navy.mil/7212
SPOT 1-2-4	MS	60 km	20 m	MS	http://www.spot.com
SPOT 1-2-4	Pan	60 km	10 m	Pan	http://www.spot.com
SPOT 5	MS	60 km	10 m	MS	http://www.spot.com
SPOT 5	Pan	60 km	5, 2.5 m	Pan	http://www.spot.com

Table 2: Characteristics of representative airborne and spaceborne instruments used in imaging the coastal zone. HS is hyperspectral, MS is multispectral and Pan is panchromatic. The listed systems are currently on orbit except COIS which is proposed to be launched in the next three years. See the listed web pages for additional information.

Existing sensors (Table 2), for example, MERIS and MODIS have the appropriate signal-to-noise ratio and a suite of spectral bands for open ocean waters plus additional bands suitable for measuring chlorophyll fluorescence, suspended sediments and for atmospheric correction over coastal waters. Imaging at 1 km resolution allows for imaging an entire continental shelf and is particularly useful for addressing large-scale ocean forcing, such as El Niño effects, on coastal ocean dynamics.

Closer to shore and in bays and estuaries, features are smaller and change more quickly (Figure 1). Higher spatial resolution sensors with a Ground Sample Distance (GSD) on the order of 100 to 300 m area required. These intermediate resolution systems are sufficient for many coastal ocean applications that require the imaging of dynamic water features such as fronts and red tides. The high resolution modes of MERIS (300 m) may be particularly useful for studies of coastal features that require better than 1 km resolution, but also large area coverage. These features vary in time and space in response to weather and tides and a geostationary satellite instrument with 300 m or better resolution and the ability to revisit a site as frequently as every 30 minutes would be ideal for studies of fronts, river plumes, red tides or other dynamic features. This would be particularly useful for ecological forecasting of the coastal ocean for a couple of reasons. First, the physical models tend to require high (time and space) resolution data to minimize forecasting errors, much like weather simulations. Second, the biological response to the physical and chemical properties of the water column is on order of minutes to hours. A daily satellite pass at a 1 km resolution frequently misses important ecosystem structure and dynamic biomass change (e.g., vertical migration of dinoflagellates) that is necessary to initialize and validate predictions in the coastal zone.

Imaging areas that include coastal or bottom features or manmade objects, such as fish farms, require 30 m or better resolution. In addition, the system must have many narrow spectral channels and a high Signal-to-Noise Ratio (SNR) suitable to distinguish and separate the various constituents in coastal water applications. Airborne imaging spectrometers (also called hyperspectral imagers) have been used to demonstrate the utility of this approach. Two systems have been used extensively over the past decade. The Airborne Visible InfraRed Imaging Spectrometer (AVIRIS, Vane, et al, 1993) a NASA facility instrument which provides very high SNR data over the 400 to 2500 nm spectral range in 220, 10 nm wide spectral channels. Typically AVIRIS is flown on a ER-2 providing 20 m GSD data which is excellent for imaging the shallow coastal ocean (Figure 2). The Portable Hyperspectral Imager for Low-Light Spectroscopy (PHILLS, Davis, et al., 2002) is a compact portable system covering the 400 to 1000 nm spectral range with 128, 4.15 nm spectral channels. PHILLS is a very high SNR system designed specifically designed for imaging the coastal ocean. There are several PHILLS instruments which are flown on a variety of platforms to give 1 to 8 m GSD data (Figure 1b).

As mentioned above, the coastal ocean is very dynamic and resolving some processes, e.g. tides and diurnal wind forcing require several samples per day. However, achieving this temporal resolution is often a function of

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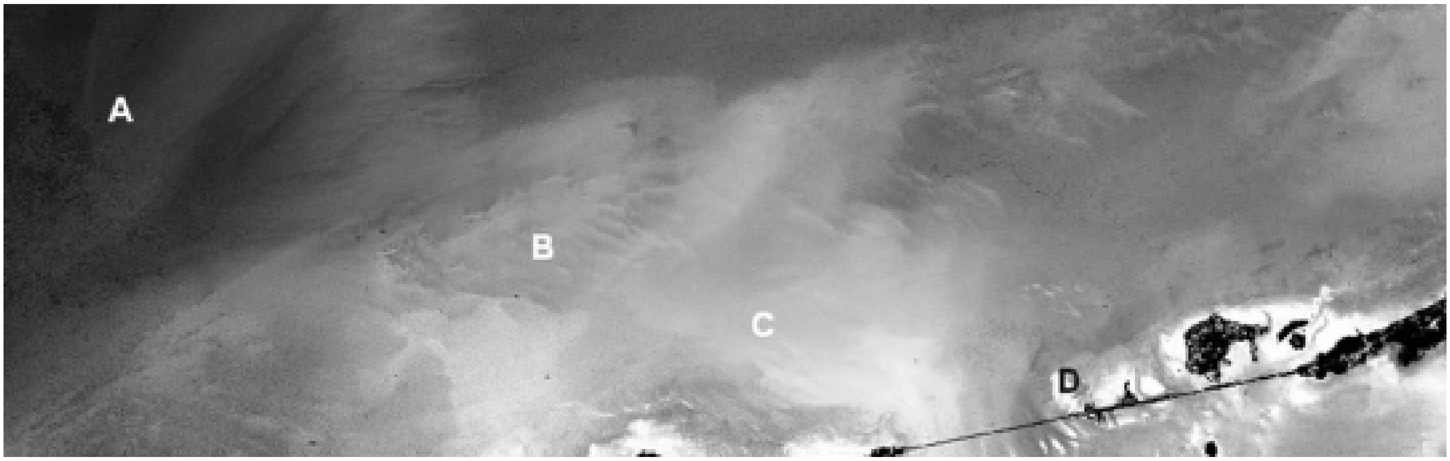

▲ **Figure 2.** AVIRIS 20 m GSD image of the Florida Keys. The image is 11 km wide and 36 km long, showing sand bottom (A,B,C) and a shallow reef (D). The water is very clear except for a cloud of suspended material around C that is coming out of the pass at the bottom of the image to the left of D. The Keys Highway connects several islands in the lower right corner of the image. Using Current algorithms (e.g. Lee *et al.*, 2001) this type of data can be converted to detailed maps of bathymetry, bottom type, and water column properties.

Optical remote sensing, *from page 5*
the remote sensing platforms altitude. This relationship can be summarized as:

- •A single polar orbiting satellite will give at best one image every 2-3 days.
- •Two polar orbiters can give daily coverage
- •An imager on a geo-stationary satellite could give 30 minute or less repeat coverage for areas in its field of regard
- •Aircraft are suitable for special studies which require frequent resampling of a particular site or feature

Thus, a mix of sensor systems will be required to properly image the full range of processes and features found in the coastal ocean. Nested sampling, using one sensor to obtain large area coverage at 300 to 1000 m resolution for context and another sensor to provide 100 m or higher resolution imaging for detailed studies of the feature of interest, may be particularly useful to provide a balance the needs of temporal and spatial resolution.

Sampling schemes should always be planned assuming that considerable data will be lost due to cloudiness. The global average cloud cover is 50%, therefore a good first estimate is to plan to sample at least twice as often as minimally required for the planned experiment or application. Geostationary imagers, which can sample every 30 minutes, provide an additional advantage in cloudy regions making it possible to sample during short breaks in the clouds.

Currently available systems and their uses

The approximately 1 km images of the Sea-viewing Wide Field of View Sensor (SeaWiFS) and the Moderate Resolution Imaging Spectrometer (MODIS) adequately image the larger features on the continental shelf and in the open ocean. Excellent use is being made of these products. Phytoplankton chlorophyll and productivity, water clarity and other products are routinely produced from this data for a variety of applications including Naval operations, fisheries and global carbon modeling. Information on these and other sensors used for characterization of the coastal ocean can be found in the web sites listed in Table 2.

As noted previously, the spatial resolution, field of view, and sampling frequency requirements of sensors for coastal waters are closely related to the planned application (Table 1). In the near coastal regions, airborne instruments, such as AVIRIS and PHILLS, and satellite instruments, such as Landsat Thematic Mapper (TM) and Satellite Pour l'Observation de la Terre (SPOT), with their high spatial resolution, have been used for mapping shallow bottom features and, manmade objects and adjacent land areas.

Currently available satellite systems, such as SPOT and Landsat have moderate SNR and broad spectral bands designed for the brighter land signals. Because of the spectral properties of water and phytoplankton absorption, and the fact that water is a very dark object, these land sensors are not well suited for coastal ocean applications. For example phytoplankton absorb strongly in the blue and backscatter in the green. Changes in the blue/green ratio are used to estimate phytoplankton abundance with narrow band sensors, such as MODIS or hyperspectral imagers. However, both the blue and green are combined as the first band in Landsat and SPOT data, and there is no way to detect changes in this key parameter.

Spectrally, approximately eight spectral bands are adequate to image large oceanographic features (IOCCG, 1998). However, additional bands may be required for more complex scenes that include sediments or bottom reflectance. To assess this issue of spectral resolution and scene complexity, Lee and Carder (2002) used remote-sensing reflectance data collected for a wide range of optically shallow and optically deep ocean environments. The data were collected at 2 nm resolution, binned to 5 nm, 10nm, 20 nm and MERIS, MODIS and SeaWiFS channels, and analyzed according to the procedures outlined in Lee *et. al.* (2001). They match the measured spectral radiance to a semi-analytic model of the water column and bottom optical properties and then minimize the least squared error between the measured radiances and model values to estimate the bathymetry, bottom and water column optical properties. For this study the results with the 5 nm data was considered truth. When results derived from the 10 nm data were compared against those obtained from the 5 nm data, they were virtually identical. Results estimated with the 20 nm data and the MERIS data channels were comparable to the 5 nm data results for deep water, but not as accurate for shallow water when the bottom was visible. The MODIS and SeaWiFS data channels did not provide accurate retrievals of bathymetry, however both performed well for deep water samples. These results suggest that multispectral systems with the standard ocean color bands (IOCCG, 1998) are fine for large scale imaging of the open ocean and continental shelf. However, when the bottom contributes to the water-leaving signal, an imaging spectrometer with 10 nm or better spectral resolution is preferred.

Future coastal imaging systems

Given the continued availability of 1 km resolution imagers, such as MODIS, two additional observing systems would be required to adequately observe all the temporal and spatial scales of processes and events characteristic of the coastal ocean. For nearshore environments, particularly when imaging the bottom and adjacent land areas, a high resolution system with a ground resolution of 20 to 30 m is required. The system should be a hyperspectral imager to resolve the spectral complexity encountered when viewing the bottom. The second imager would be moderate resolution (100 to 300 m) with a 200 km swath to cover the entire continental shelf.

The U.S. Navy has a strong interest in near coastal measurements and has invested in the development of the Coastal Ocean Imaging Spectrometer (COIS), Wilson and Davis, 1999). COIS is a hyperspectral satellite instrument that is designed to meet the requirements for measuring shallow water optical properties, bottom type and bathymetry. It has high sensitivity and a very high SNR to image the coastal ocean at a 20 m GSD from a 400 km orbit. The swath width is 1000 pixels and a standard scene would 20 km x 100 km. It uses an Offner spectrometer design and a 1024 x 1024 pixel thinned backside-illuminated CCD camera to achieve the required sensitivity in the blue.

The primary goals for COIS are to map shallow water bathymetry and bottom characteristics at 20 m spatial resolution and to measure CDOM, phytoplankton and suspended sediments in a wide range of coastal environments. It was originally planned to fly COIS on the Naval Earth Map Observer (NEMO), Wilson and Davis, 1999) as part of a joint program between the U.S. Navy and a commercial partner. That program was not completed due to lack of commercial funding. The current status is that a COIS engineering model has been completed and tested to demonstrate that the design meets all of the science requirements. The flight instrument is approximately 70% complete. However, the Navy remains interested in completing and flying COIS and they are looking for another opportunity to fly the COIS sensor through the Department of Defense Space Test Program.

There are additional requirements for water column properties at a somewhat coarser resolution. Navy, NOAA, and university researchers are developing dynamical models to forecast physical properties (temperature, salinity, and currents) and optical properties at resolutions of 100 to 300 m for the coastal ocean. Visible radiation is the only electromagnetic tool that directly probes the water column, and so models of visibility are key to naval systems for bathymetry, mine hunting, submarine detection, and submerged hazard detection. Physical models also need Sea Surface Temperature (SST) at the same resolution for model initialization and to track the physical mixing processes that affect the optical properties. A Visible-Near Infrared Red hyperspectral sensor with a co-registered SST sensor with 100 m spatial resolution would provide essential data for the development, initialization and updating of these models.

NOAA is developing the Coastal Global Ocean Observing System (C-GOOS) to monitor the health of the coastal ocean, including providing warnings of harmful algal blooms, assessing changes in water clarity, biodiversity and the growth of non-indigenous species (Malone and Cole, 2000). A 100 m resolution hyperspectral sensor with a co-registered SST sensor will provide the synoptic view to complement the planned mooring and ship based measurements and give a coherent picture of the coastal ocean. The 100 m resolution is 10 times that of the global ocean color imagers and sufficient to image red tides, fronts, bays, estuaries and other features of concern for coastal management while still providing a broad 150 km wide swath along the coast.

To meet those Naval and NOAA requirements the Integrated Program Office (IPO) is considering flying the Coastal Ocean Imager (COI) as part of the Ocean Observer satellite. The idea behind the Ocean Observer is to supplement the regular National Polar Orbiting Environmental Satellite System (NPOESS) satellites with additional sensors that focus on the coastal ocean. COI is a moderate resolution hyperspectral imager -which is proposed as part of Ocean Observer. COI would have 64, 10 nm wide spectral channels covering the 380 – 1000 nm spectral range, and two IR channels in the 10 - 12 mm range for SST. Recent improvements in array detectors make it possible to extend down to 380 nm to detect signatures of oil spills and red-tide dinoflagellates. It would have 1500 pixels across track and a scanning telescope that would allow it to follow the coast line and sweep a 150 km wide swath that tracks the coast. It would have a +/ 45 deg field of regard which allows 2 day revisit to any coastal region. It would be a small compact instrument using proven designs and already space qualified components to minimize cost. This high resolution system would make the Ocean Observer

— continued on page 8

Optical remote sensing, *from page 7*

a valuable system for dynamical models of the coastal ocean and for optical and biological applications essential for Navy and NOAA missions.

In addition to establishing an observing system that matches the fine spatial scale of coastal environments, a second system is required to provide higher rates of coverage in order to fully address the hourly to daily scale events of this region. Daily coverage at a fixed local time (near noon) provided by polar orbiting satellites is inadequate to resolve key underlying processes such as tides and local wind forcing which operate at shorter time (hours to days) scales. More frequent observations are required to remove the effects of tides and to validate tidal mixing terms in coastal ecosystem models. To study short-term events, data from polar orbiting sensors need to be augmented by comparable data with a higher rate of coverage.

One feasible approach would be to place a Visible Near Infrared (380-1000 nm) imager on a geostationary platform. Due to the great distance of a geostationary platform from earth, this approach would limit the spatial resolution to approximately 250 m or greater. It would, however, provide the capability to rapidly revisit to regions of interest greatly improving the input to models and the tracking of red tides and other features of interest.

Several systems designed to remedy coverage constraints imposed by polar orbiting platforms have been proposed. Studies have been conducted to show the feasibility of a high spatial resolution (250 m), 18 - 20 channel multi-spectral, instrument covering the UV-visible- near infrared (313 - 905 nm) spectral range. This instrument could provide observations on a regional level as frequently as every 15 minutes from Geostationary Operational Environmental Satellite (GOES). High spectral resolution hyperspectral imagers have also been proposed for geostationary orbits. These instruments are designed as atmospheric sounders, and tend to have courser spatial resolution, but they may be adapted for dual use for imaging the coastal environment.

The high temporal and spatial resolution data from a geostationary sensor would uniquely fill an existing gap in the time-space domain of observations of the coastal ocean facilitating studies of short-term events and processes of the coastal ocean, land, and atmosphere. These data will permit the investigation of processes of the dynamic coastal ocean, such as tidal mixing, as well as the study and tracking of ephemeral events in the terrestrial and atmospheric environments, including storm development, volcanic ash plumes, and motions of atmospheric pollutants (smoke, dust, and sulfate aerosols).

A problem with once-a-day sensors is that clouds often degrade the number of usable pixels from a scene of interest. However, the motion of clouds can be used with more frequent measurements from a geostationary satellite, to effectively increase the number of cloud-free observations in a region of broken clouds through cloud filtering and compositing of multiple images. These attributes will strengthen our ability to appraise local conditions and predict short-term events. Augmenting nearly continuous observations from geostationary platforms, with higher spectral resolution data from polar orbiters, will allow the investigation of oceanic processes not possible with either platform separately. Geostationary imagers can also be used to extend the temporal window seen in intermittent observations from very high spatial resolution ocean color sensors like COIS.

Conclusions and future directions

The current remote sensing systems, such as Landsat and MODIS, have a long heritage that began in the 1970s. Forward looking engineers and scientists designed suitable instruments and analyzed their data, pushing relentlessly for more and improved sensors. That process has continued for 25 years and has led to the systems we have today.

The same long-term and dedicated effort is required to develop, launch and demonstrate the utility of imagers necessary to observe and monitor the coastal ocean. Over 60 % of the world's population lives along the coast and human activity greatly impact the coastal ocean. A coordinated program to monitor and protect these precious coastal waters is needed. Achieving that program will require a coordinated effort to fund, build and demonstrate the utility of the required infrastructure including, dedicated satellite systems, *in situ* monitoring systems and modeling of the coastal ocean.

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World Ocean Circulation Experiment global data DVD suite

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The World Ocean Circulation Experiment (WOCE) is the part of the World Climate Research Program that has used resources from 30 or so countries to make unprecedented *in situ* and satellite observations of the global ocean. It is the first comprehensive global ocean data collection program that has been conducted during the past decade. The US National Oceanographic Data Center (NODC), in cooperation with the WOCE Data Products Committee (DPC), has produced a series of suites of CD-ROMs/DVDs for each type of the WOCE data. The first version was produced on CD-ROM in 1998 and Version 2.0 on CD-ROM in 2000. Since the issue of the WOCE Version 2 data on CD-ROM, the WOCE DPC has been considering the possibility of distributing the WOCE Version 3 data on a small number of DVDs rather than a larger number of CDs. In practical terms it would clearly be an advantage to have all the WOCE data on 2 DVDs rather than 26 CDs. The DPC-15 meeting at Australia Commonwealth Scientific and Industrial Research Organization (CSIRO) in Hobart, Australia, decided that DVD media would be most advantageous for distribution of Version 3.0. The final set, WOCE Global Data, Version 3.0, was subsequently produced in August 2002 and distributed to approximately 400 participants of the *WOCE and Beyond* Conference in San Antonio, Texas, November, 18 - 22, 2002 (WOCE Data Products Committee, 2002).

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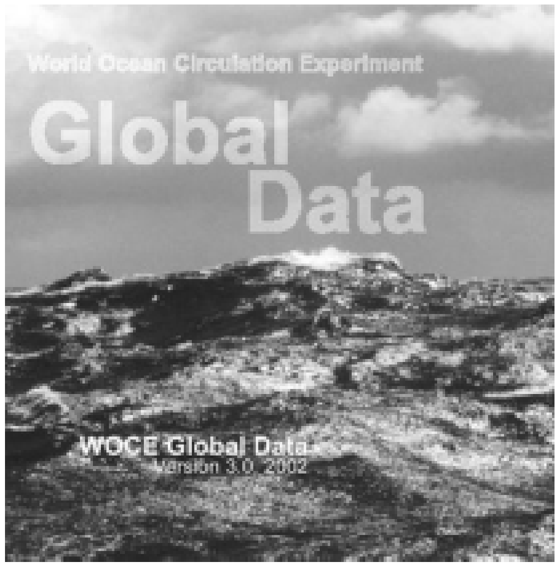

This is one of the first times a major science program has adopted DVD media for publically distributing its data. The primary purpose of this article is to describe the contents of the WOCE Global Data DVD. Experiences learned from the production of the DVDs are also presented here.

WOCE structure

The structure of WOCE is a distributed system which consists of several elements with the flow being from Principal Investigators to Data Assembly Centers (DACs), to Specialized Analysis Centers (SACs), to users and then to Archive. In addition, the Data Information Unit (DIU) maintains information on the status and location of WOCE data sets and the International Project Office (IPO) publishes a newsletter, about 4 times per year, reporting recent results concerned with observations, theory, and models of the ocean. IPO also publishes reports from conferences and Workshops. Each type of WOCE data, a “data stream’, was accumulated at a DAC that had specialist knowledge of the particular kind of data. The WOCE data streams were: Bathymetry, Current Meters, Drifters, Hydrography, *In Situ* Sea Level-Fast Delivery, *In Situ* Seal Level-Delayed Mode, Profiling Floats, Satellite Sea Surface Height, Satellite Sea Surface Temperature, Satellite Surface Winds, Sea Surface Salinity, Shipboard Acoustic Doppler Current Profilers, Subsurface Floats, Surface Meteorology, and Upper Ocean Thermal. In addition, two SACs, Hydrographic SAC and Surface Fluxes SAC, were formed to generate gridded fields from hydrography data and air-sea flux products from meteorological data, respectively. The US NODC is the long-term repository of the WOCE data. Although WOCE’s observational phase ends in 1998, many data sets will still be processed after that time. Some sources will be producing WOCE data through 2002. For example, float and drifter data from deployments in the 1990s will continue to be acquired to contribute to the required five-year average; some current meter arrays will be awaiting recovery, while some data streams will be continuing and in the process of transition to other climate programs. The repeat hydrography and XBT programs, which are integral parts of WOCE’s assessment of variability, will be continued under funding outside WOCE. Some DACs, for examples, current meters and subsurface floats, ended their operations. The DIU and IPO will be closed after the final conference of the WOCE program. DIU’s web site will be moved to and installed at the NODC. The new web address of DIU is *http://www.nodc.noaa.gov/wocediu*.

DVD contents and data format

The WOCE Global Data DVD suite consists of two single-sided and double-layered DVDs. Each of contains a series of directories (also known as folders). A Web browser is required for exploring and accessing their contents. At the top

— continued on page 10

WOCE DVDs, *from page 9*
level of both of the DVDs (the "root" directory) are identical copies of introductory files (web pages) prepared by DIU. Below this level are more directories containing the data files and documentation for each WOCE data type. The introductory pages provide tools and software, which are needed to search and locate data files or unzip files. They also include links to each data directory, where an index or welcome pages allows users to explore their contents. Table 1 summarizes the data content of the WOCE Global Data Resource Version 3.0 as published on DVD.

The data on these disks cover most of the global ocean and are from the period of 1990 to 1998, the intensive observation phase of WOCE. Some data are included before and after this period. All the data are scientifically quality controlled by each DAC and SAC and are accompanied by documentation that explains collection and quality control procedures. They are provided in the netCDF (network common data format) format. Many are also provided in ASCII. The use of netCDF allows the WOCE data to be platform independent for direct access to the data and determine its structure, the variables' names and essential metadata such as the units. The standards for netCDF files have been implemented and recognized internationally, namely, the WOCE data are readable through may commonly used software packages, such as "*ncBrowse*" (Denbo, 2001). A netCDF primer, "*A First-Time Users Guide to netCDF*" can be found on the Help pages of the disks. The Primer provides guidance on how to view, plot and manipulate the data.

A very useful tool, known as "*eWOCE*", on Disk 2 provides global or basin-wide data collections for most WOCE data streams for usage with the Ocean Data View (ODV) (Schlitzer, 2000). Included are ODV installation files and runtime environments for Windows, Max OS X, Linux, Solaris, Irix platforms. The runtime environments enable ODV to run directly from the DVD without the need to install the software first.

The contents of the WOCE Global Data DVD set is available on-line at *http://www.nodc.noaa.gov/woce_v3*. Following the production of the DVDs, updates and amendments to the contents will be posted online.

What have we learned?

DVD once stood for digital video disc or digital versatile disc, but now it just stands for DVD. It is essentially a bigger, faster CD that can hold cinema-like video, better-than-CD audio, and computer data. It is important to understand the difference between the physical formats (such as DVD-ROM or DVD-R) and the application formats (such as DVD-Video or DVD-Audio). DVD-R is the base format that holds data. A basic DVD-R, also known as DVD-5, comprises a single layer with a capacity of 4.7GB. This is the simplest of the family of DVD disks. The WOCE DVD uses the single sided (SS) and dual-layer (DL) version of DVD-R, which has a capacity of 8.5GB, and as such can only be replicated by commercial companies using expensive equipment. The combination of SS and DL would not require manual flipping by the users.

The major drawback has been the lack on standards for DVD printing and reading. The file systems used by major operating systems, for examples, Unix, Linux, Windows, and Mac OS, are different. The most popular one is specified by the international standard ISO

— continued on page 12

Table 1. Summary of the data content of the World Ocean Circulation Experiment Data DVDs

Measurement Type	Folder Size (MB	Number of Folders	Number of Files
Disk One			
Current Meters	608.0	657	10,601
Profiling Floats	30.5	15	92
Shipboard ADCP	325.0	526	6,537
Sea Surface Salinity	51.3	154	3,902
Sub-surface Velocity	183.0	35	587
Hydrography	1607.8	845	6,794
Air-Sea Fluxes	485.0	144	9,379
Surface Meteorology	448.0	584	9,000
Sub-surface Floats	80.5	5	483
Upper Ocean Thermal	1065.0	68	1,300
Disk Two			
Bathymetry	258.0	4	308
eWOCE	292.9	121	2,399
Satellite Surface Winds	886.0	222	15,656
Satellite Sea Surface Ht	523.0	17	2,406
Satellite Sea Surface Temp	244.0	12	3,581
Sea Level (Fast Delivery)	508.0	32	6,715
Sea Level (Delayed Mode)	605.0	16	3,098
	8201.0	3457	82,838

Data products and services

New U.S. Climate Atlas now available

The new CD-ROM (version 2.0) of the *Climate Atlas of the United States*, which contains climate maps for all 50 states, is now available from the National Climatic Data Center. This atlas replaces the popular paper copy of the *Climatic Atlas of the United States*, published in 1968, and supersedes the Climatic Atlas of the Contiguous United States CD-ROM (version 1.0), which was published in 2000. The new atlas contains over 2000 maps which depict temperature, precipitation, snow, and other parameters for all areas of the U.S. and includes Alaska and Hawaii, which were not on the version 1.0 CD-ROM. The station data for 7700 locations used to produce the atlas maps, along with detailed documentation, are also contained on the CD-ROM.
Contact: NCDC

International Seabed Authority (ISA) Central Data Repository

The United Nations-sponsored ISA has just released its new marine minerals Central Data Repository online. Currently, the repository consists of geochemical data on polymetallic nodules and ferromanganese crusts obtained from the NOAA and Minerals Management Service (MMS) Marine Minerals CD-ROM data set; this was produced by NGDC in cooperation with NOS (NOAA's National Ocean Service) and MMS in 1992 from a decade-long collaboration.

The ISA has reformatted data from the original CD-ROM and is offering it on the web, citing NGDC as the original compiler. The ISA intends to archive the public portions of their new Central Data Repository at NGDC through the mechanism of the World Data Center for Marine Geology and Geophysics, Boulder.
Contact: NGDC

Nighttime lights featured

NGDC's Nighttime Lights of the World were featured on the cover of the September-November (volume 39) issue of the *UN Chronicle* special issue titled "Sustainable?" The issue and cover are available online at *http://www.un.org/Pubs/chronicle/2002/issue3/0302cont.htm*.
Contact: NGDC

GOES SXI archive and public interface

Several major milestones were reached in the FY02 phase in the development of the Geostationary Operational Environmental Satellite Solar X-Ray Imager (GOES SXI) archive and public interface. Software was completed permitting users to browse, summarize, and search SXI data. Software to generate and access movies of all SXI images was also completed. Hardware has been integrated into the system that will permit the online storage of all browse imagery. Archival and retrieval of SXI images is accomplished through a tape robotics system. The 100,000 images collected during the Post Launch Test phase have been used to test all phases of development and are currently available through the public interface at *http://sxi.ngdc.noaa.gov*.
Contact: NGDC

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E-mail: help@esdim.noaa.gov
WWW: *http://www.eis.noaa.gov/*

NOAA Central Library
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Fax: 301-713-4599
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WWW: *http://www.lib.noaa.gov/*

NOAA providing data for oil spill in Spain

On November 21, 2002, NOAA received an official request from the Government of Spain for assistance with the oil spill from the tanker *Prestige*, which broke up and sank off the coast of Spain on November 18. In support of that request, the National Satellite Data and Information Service (NESDIS) is acquiring synthetic aperture radar (SAR) data and will provide the analysis for the National Ocean Service response and restoration efforts. The SAR data provides imagery showing oil location and extant, and can also show water currents so as to assist with assessment of spread. Additionally, NESDIS is providing available marine data and near-coastal surface data for Spain and Portugal to NOAA's Hazardous Materials (HazMat) office. The data were requested to provide a climatology for long-range forecasting. Using the historical wind data extracted from National Climatic Data Center's databases, the HazMat team can sample the data to ascertain the probabilities of oil moving in various directions.
Contact: ESDIM

New image products available through SSM/I browse system

A new version of the National Climatic Data Center's Special Sensor Microwave Imager (SSM/I) Browse System was placed online to provide access to a significant number of new climate products that are derived from the SSM/I, a polar-orbiting satellite with global coverage. These new products include weekly and monthly anomalies and full fields for surface wetness, temperature, and snow cover for 11 regions around the world from the period January 1988 to the latest available week. Global-gridded data files are also now accessible through the system for each SSM/I product. In all, over 57,000 images and 4000 data files are available. In addition, a new JAVA looping feature has been added to the system which allows users to view an animated loop tailored to their specifications. The SSM/I Browse System was created, and is currently maintained, via a cooperative effort involving personnel from NCDC's Data Access Branch and the Climate Analysis Branch.
Contact: NCDC

WOCE DVDs, *from page 10*

9660. This standard specifies a very minimal file system, which every operating system should be able to map it to its native system. However, for normal Unix use, the ISO 9660 file system is not usable. Unix only supports an extension to the standard, called the Rock Ridge extension. Rock Ridge allows longer filenames and symbolic links. Rock Ridge file system is still a valid ISO 9660 file system, making it usable by non-UNIX systems as well. Linux supports both ISO 9660 and the Rock Ridge extensions; the extensions are recognized and used automatically. However, the technology for creating a DVD with Rock Ridge extensions was not reliable at the time when the WOCE DVDs were produced, we feel it is best to follow the path of creating the DVDs using the ISO/UDF (Uniform Data Format) bridge option with it's 8-level and 32-character file naming convention limitations. The ISO/UDF format is the only format which assures compatibility across different platforms and Operating Systems. The drawback for Unix users is it should be mounted as a UDF file system. Despite extensive efforts, it has not been possible to master the DVDs with Rock Ridge (RR) extensions. There is plenty of mastering software for single-layer DVDs with RR extensions, but only one that we have found that could be utilized by the replication company to produce double-layer DVDs with RR extensions. Unfortunately, this software did not produce a robust, stable trial disk. The disk caused various problems when mounted as "hsfs" in Solaris machines. Therefore the WOCE V3 DVDs do not have Rock Ridge extensions and the current releases of Solaris do not mount it correctly. Sun is aware of the problem (of udfs disks mounting as hsfs) and it has a bug number.

Summary

The WOCE DVDs were produced on time for distributing at the *WOCE and Beyond* Conference in San Antonio, Texas, November, 18 - 22, 2002. The DVDs were a highlight of the meeting. The contents of the WOCE Global Data DVD set is available on-line at *http://www.nodc.noaa.gov/woce_v3*. Following the production of the DVDs, the US NODC continue to provide supports for updates and amendments to the contents of the DVDs. They will be posted online.

The technology for creating a DVD with Rock Ridge extensions was not reliable at the time when the WOCE DVDs were produced. The WOCE DVD uses the ISO/UDF (Uniform Data Format) bridge option with it's 8-level and 32-character file naming convention limitations. The ISO/UDF format is the only format which assures compatibility across different platforms and Operating Systems. The drawback for Unix users is it should be mounted as a UDF file system.

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Many countries, agencies, institutions, and individuals have played important roles in the creation of the WOCE Data DVDs. It is not possible to identify and thank individual sources of data here, but the most important contributors are the collectors of the original data. Without their efforts, this compilation of data and information would not have been possible.

The WOCE DPC devised the original concept of the WOCE Global Data disks, and guided their production and content. The DVD contents were constructed by the DACs, SACs, and DIU. The author is very grateful for their contribution to this package.

Thanks are also due to Ms. Shannon Niou for checking the contents of the WODC DVDs and testing their web pages' linkages. The author would also like to thank American Media International, Ltd. for DVD glass mastering, replication, and duplication of the DVDs .

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