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Editorial

I must have been in a professional funk last year. What else could possess me to write an editorial entitled "Where Have All the Flowers Gone" [*Backscatter*, 11(4), 2000].

The editorial alluded to the fact that a noticeable number of space-sector companies, employing a number of acquaintances, had either gone out of business, got out of the space sector, or were drinking red ink.

That fabulous space-based commercial market we were all looking for has not materialized. At least, not the way most hoped it would.

A healthy marine remote sensing sector did, however, develop in the 1990s. Remote sensing is now an integral component of the world of ocean measurements. We are even witnessing the birth of an "operational oceanography" sector. And the focus has moved to the coastal zone where the markets are larger and more diverse than open ocean applications.

Operational oceanography involves sensors from all the major platforms - buoys, aircraft, satellites and land-based installations. But among these, sensors mounted on buoys and deployed from ships (i.e. in situ sensors) are used most commonly. As a result, data telemetry has proven to be a key component of recent advances.

Based on discussions held during AMRS' recent board of directors meeting, the operational oceanography sector will grow this decade, globally. Will the space sector grow with it? According to articles published in this issue of *Backscatter*, and other observations, I conclude the answer is yes, but possibly by nowhere near its full potential.

There are a number of reasons why the space sector is struggling to find its place among operational users. One appears to be dominating. It is not detection, as the proponents of technology would have you believe. It is the sensor's revisit time. Sensors that revisit every few days or weeks are generally inadequate for operational applications. They are excellent for demonstration purposes, but are simply addressing the fiddly bits around the edge of the operational market.

Whether you are talking about wind, waves, currents, ship detection, ice mapping, water quality monitoring, fisheries or disaster management, invariably, operational users are saying they need updates at least daily, and in certain cases several times per day. Few spaceborne systems can meet this need, and therefore, users are putting their resources into alternative systems.

Just this week, for example, I attended a seminar on the ocean observing system that is being installed in the Gulf of Maine. Proponents have gone to great lengths to develop a diverse user community for the system. As a result, its subscribers include government agencies, private companies and non-profit groups from several New England states and two Canadian provinces. It includes state-of-the-art buoy, in situ sensor and data telemetry systems, as well as land-based HF radar installations (Codar). It is a component of a potential continent-wide infrastructrure which Evan Richert, of the State of Maine Planning Office, says will eventually cost $100 million. But it only calls for three types of satellite maps - temperature, color and wind vectors.

Of the almost 30 sensors listed on AMRS' aquatic features from satellites poster, only three have revisit times of one day or better at Maine latitudes - NOAA's AVHRR (for water temperature), Orbital Science's Seawifs (for water color), and NASA's Quickscat (for wind vectors). Coincidence? Perhaps.

Several of the authors in this issue of *Backscatter*, such as Yésou et al. in their flood mapping article, come right out and state the revisit time problem. Others, such as Hutt, allude to it by stating that narrow swath width precludes operational use. In a follow-up e-mail, Hutt writes "the long revisit time of SAR satellites is the main factor limiting their use for operational acoustic environmental assessment. A revisit time of twice per day would be pretty useful. The swath width itself is not the main problem."

Marie Colton and Lee Dantzler, from NOAA/NESDIS, sum it up rather well in their article on operational oceanography - "Building a working satellite hardware and software system does not guarantee user support or customer satisfaction. .... Reliable access to a sustained source of data with adequate coverage and refresh rates, a constellation, is necessary to entrain and hold the user community." ■

Brian G. Whitehouse - Editor.

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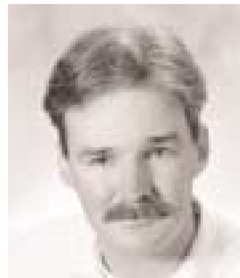
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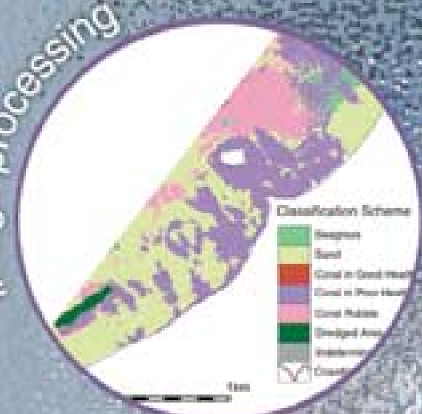

Images are courtesy of Baird & Associates and the government of St. Lucia.

Operational Oceanography in the USA
developing a strategy for NOAA/NESDIS

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Ocean monitoring using space-based assets is a critical component in the ongoing development of global ocean observing systems (Nowlin, 1999).

The past twenty years in satellite oceanography have been an era of instrument, technique and technology development in each of the major conceptual areas advanced nearly forty years ago: altimetry, scatterometry, visible and infrared radiometry and more recently, synthetic aperture radar. While most of the ocean observing instruments have been unique systems on a discontinuous sequence of research and development platforms, ocean parameters such as sea surface temperature, wind speed, ice concentration, and water vapor have been regularly measured and archived for approximately twenty years from operational meteorological satellites. Over these two decades, operational measurement of basic ocean parameters coupled with continuously improving research instruments and data accuracy has proven to be a powerful combination. End-users of satellite ocean data have become more comfortable with the reliability, interpretation, and sustained availability of remotely sensed data. Long-term use in daily applications is an essential aspect of the technology transfer process. We now see satellite data utilization in conventional oceanographic applications, growing commercial development, and improving ocean forecasting and real-time imagery.

In recent public discussion (EOS, Transactions Amer. Geophys. Union, March 14, 2000), Mooers summarizes some fea-

tures relevant to a generic operational oceanographic information system: real-time remotely sensed and in situ observations; assimilating numerical circulation models; quality control of observational data sets and models; real-time dissemination of ocean information products; user feedback mechanisms; archival of observations and model output. There are human resource requirements as well: support by a highly educated workforce for the maintenance, upgrade, and interpretation of data and forecasts; support by a diverse basic and applied research enterprise, underpinning of an educational system that continuously entrains students into the relevant engineering and geophysics professions; support by a scientific and professional society that provides a venue for public discussion of the end-to-end system.

Spinrad (EOS, Transactions Amer. Geophys. Union, June 27, 2000) comments that this type of daily operational oceanography has long been the backbone of military oceanography for the purpose of supporting national defense. However, Wilson (EOS, Transactions Amer. Geophys. Union, November 21, 2000) notes that similar daily uses have yielded viable products in the civil sector such that the civilian oceanographic community has a similar advocacy for "operational oceanography" to support its public missions of ocean and coastal monitoring and research, commerce and economic stability, civil engineering and public safety.

The list of features framing the concept of an "operational oceanography system" is drawn from an operational meteorology analogue. In this model, the historical development of meteorological satellites can be contrasted to that of oceanographic satellites and the relative strengths and weaknesses debated. However, it is also possible to consider that the two technology development pathways are, in a sense, sim-

Figure 1. *NOAA scientists arrive in Alaska to begin fine tuning new wind imaging techniques by comparing satellite and aircraft observations*

Figure 2. (a) *Ocean Optics and the Marine Optical Buoy (MOBY). (a) MOBY being deployed from the University of Hawaii's RV Moana Wave off the northwest coast of Lanai, Hawaii.*

“Building a working satellite hardware and software system does not guarantee user support or customer satisfaction.”

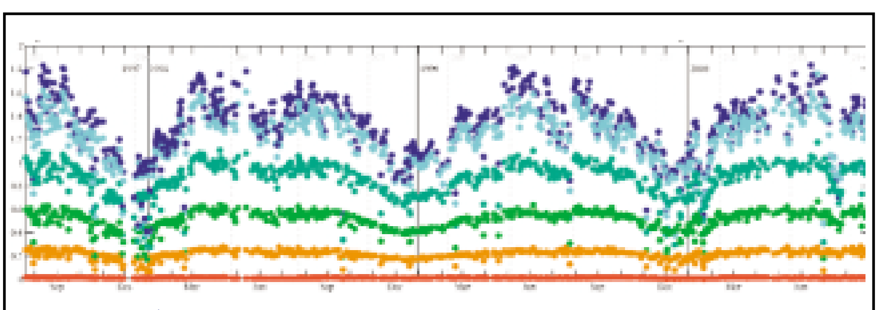


Figure 2. *(b) This graph depicts a three year time series of the water-leaving radiances at the SeaWiFS spectral bands. These data were derived from the MOBY observations acquired during the SeaWiFS overpass times and used to initialize the calibration for monitoring the sensor's long-term stability.*

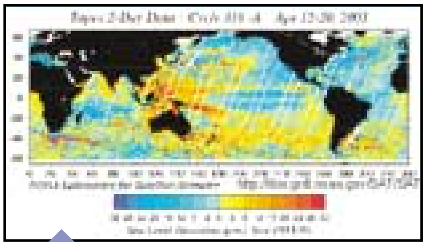
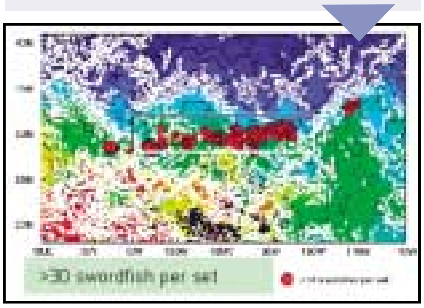
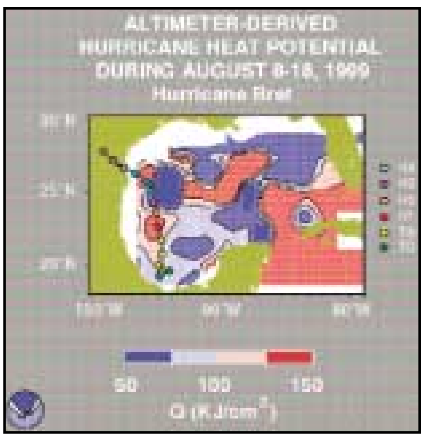


Figure 3. *Operational applications of altimetry data for ocean model assimilation, climate modeling and monitoring hurricane intensification and fisheries.*





ply transforms of each other such that there are advantages and disadvantages to each view. Furthermore, even though satellite meteorology and oceanography did not start at the same technological origin, they are inextricably linked sciences such that neither is truly independent of the other.

The continuous operations of NOAA TIROS and DMSP meteorological polar orbiting satellites flying in constellation, coupled with geostationary satellites and international assets, has produced decadal time series of global ocean observations from a consistent set of instruments, leading to standardized algorithms and products. The price of continuity is often a programmatic and technological conservatism. Alternatively, ocean sensors on research platforms launched at discrete intervals offer important complements to continuous systems, and have contributed to meteorology by supplying necessary surface conditions such as ocean wind vectors.

Ocean sensor ground processing systems have allowed for adaptation to the rapid development of the Internet, commercialization, open systems and the anonymous user. For example, the Coastwatch development was an open systems design from inception and used the Internet to distribute remotely sensed ocean data five years ahead of NESDIS meteorological operations (http://coastwatch.noaa.gov/COASTWATCH). Value-added commercialization of data began with the Freedom of Information Act in 1994, and today there are 6,000 to 8,000 registered commercial Coastwatch users. Incorporating new technology into current operations in a rapid development mode often occurs at the expense of standardization and infrastructure for a steady and known, high-volume, customer base. Thus, a close synergy is required between the research and development and operational communities.

In effect, the operational meteorological and oceanographic research satellite developments mirror the old and new economies of today and the most appropriate lessons and features of each need to be considered in the design of "operational" satellite oceanography. Building a working satellite hardware and software system does not guarantee user support or customer satisfaction. Operational customers are often "late adopters" and need time and training to become informed users and advocates. That being said, today's user has a much shorter time horizon than a decade ago. To bridge the gap quickly, there must be continuous support for applied scientists and engineers who maintain the system and provide customer service. These same scientists, the products they develop, and the provision of customer service are reinvigorated by regularly connecting the application and its interpretation to its physical basis through regular fieldwork and *in situ* validations (Figures 1 and 2).

The role that national-level data centers play in operational oceanography (satellite and conventional) is rapidly evolving. An expanding, increasingly diverse and sophisticated set of users has direct Internet access to a growing base of digital oceanographic and marine meteorological data. Effective use of these real-time observations requires the complete data record (historical and present) to be available online. The data centers are therefore seeing online data access and automated archival operational requirements entering their day-to-day business.

Databases are also being integrated into a fabric of distributed databases across the U.S. and around the world. As the data move from the federal to local level, commercial opportunities must be considered, as well as local user requirements for data access, usually in a native geographic information system format. Real-time Internet access with quality assurance, interpretative statements and online virtual training methods are becoming standard requirements.

All of the system and user components discussed above do not emerge simultaneously, are not necessarily sequential, and the feedback among components is nonlinear and ongoing. In short, as the corporate world understands, today's new operations must have a carefully crafted "business plan". NOAA/NESDIS is actively engaged in the conversations among possible collaborators, which are becoming more frequent and are now focussed on definition of an integrated operational infrastructure that includes satellite oceanography and requirements for long-term, *in situ* observations (GODAE Report No. 6, 2001, see "References" for details).

As these designs and relationships evolve over time, the powerful combination of research satellites and associated computational platforms set within an operational framework provides an essential tool for exploring and evaluating operational concepts, training personnel, and preparing user foundations to accept new data types. For example, in 2001, NESDIS co-sponsored a topical call for altimeter and scatterometer operational demonstrations within the National Ocean Partnership Program. Two supporting educational measures are also being undertaken: the establishment, via competitive process, of a NESDIS Cooperative Center for Ocean Remote Sensing, and a NOAA Center for Remote Sensing supported by a new Minority Serving Institution initiative. The NESDIS Ocean Remote Sensing program is an annually announced competitive program that awards grants to academic and other institutions for remote sensing research relevant to the NESDIS satellite oceanography mission. Finally, a Joint Center for Satellite Data Assimilation between NASA and NOAA was initiated to accelerate satellite data utilization within the numerical modeling community. These activities are investments in the future critical operational elements of optimum data utilization, user interactions, and long-term education and academic tie-ins.

With its domestic and international partners, NOAA/NESDIS presently supports data streams, research and operational applications of altimetry (Figure 3), scatterometry (Figure 4), visible, infrared, and microwave radiometry and synthetic aperture radar. Among other parameters, these instruments deliver near real-time sea surface height, wind, temperature, and color, which are used very effectively with in situ data to characterize dynamical features associated with important fishing stocks [see Hawaii Coastwatch node for real-time examples]. Once exclusively in the domain of ocean signature research or ice applications, high-resolution synthetic aperture radar imagery is finding favor in the coastal and fisheries management communities (Figure 5).

Quasi-operational satellite oceanography systems accelerate progress and are insurance against artificial conservatism. All of the experimental systems have Web-based interfaces and operational users who

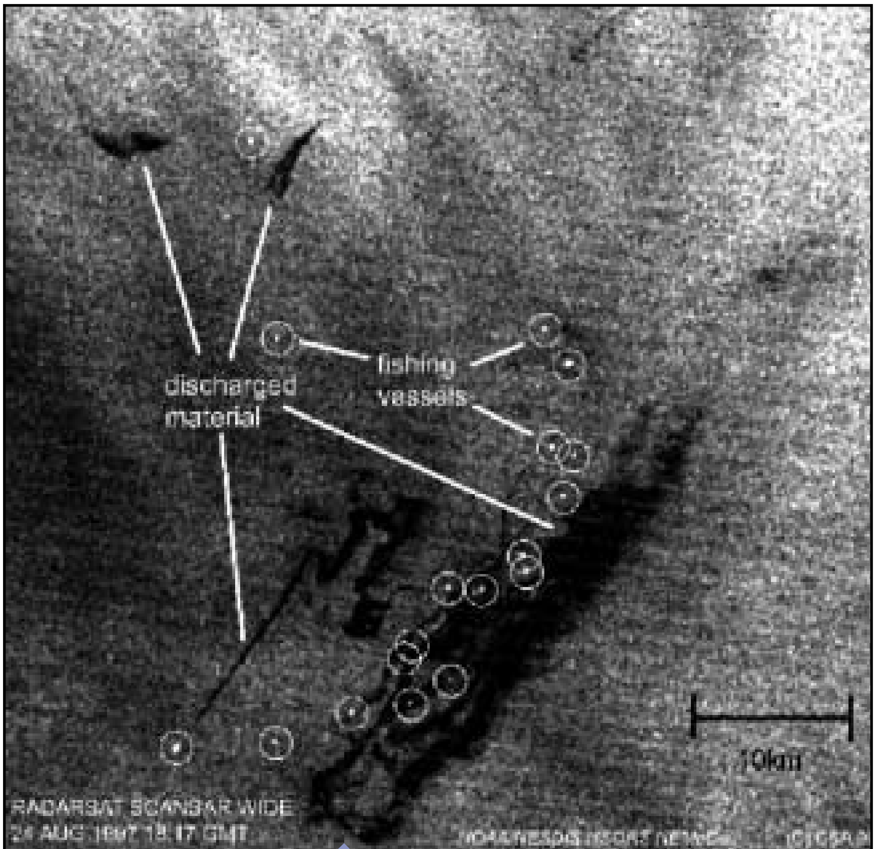


Figure 5. *AKDEMO: A pre-operational demonstration of near real-time coastal and marine SAR products for Alaskan waters.*

continuously monitor and evaluate the near real-time, experimental products. The results show that what is needed is limited invention of new approaches, and greater integration, efficiency, and extension of existing distributed systems. Reliable access to a sustained source of data with adequate coverage and refresh rates, a constellation, is necessary to entrain and hold the user community. Deliberate phasing of funds and joint risk-reduction efforts between the research and operational data providers optimize transitions.

Evolution of ocean data center archives from a pure repository to an online service provides ocean contexts where there were few before. Within these contexts, tactical applications, integration of data types and dissemination as Geographic Information System (GIS) data layers allow satellite data utilization at a local level. Especially at this level, an optimum combination of private and public assets helps justify national expenditures and ensure long-term success by helping bring products to market. Clear definition of data exchange policies is crucial in dual-use and international collaborations (Figure 6).

The challenges identified by the activities illustrated above are numerous but technically achievable and require dedicated partnerships among satellite data providers, the modeling community, and users. A guide to the future is found in analysis of previous meteorological and oceanographic satellite developments interpreted within today's Internet context of rapid evolution and interactive user participation. For maximum utilization of prototypical sensors, NESDIS is making significant investment in commercial data buys, real-time processing, telecommunications and storage technology in support of national and international access and distribution of ocean sensing environmental satellites. NESDIS is further contributing to the positive momentum for operational satellite oceanography through grassroots

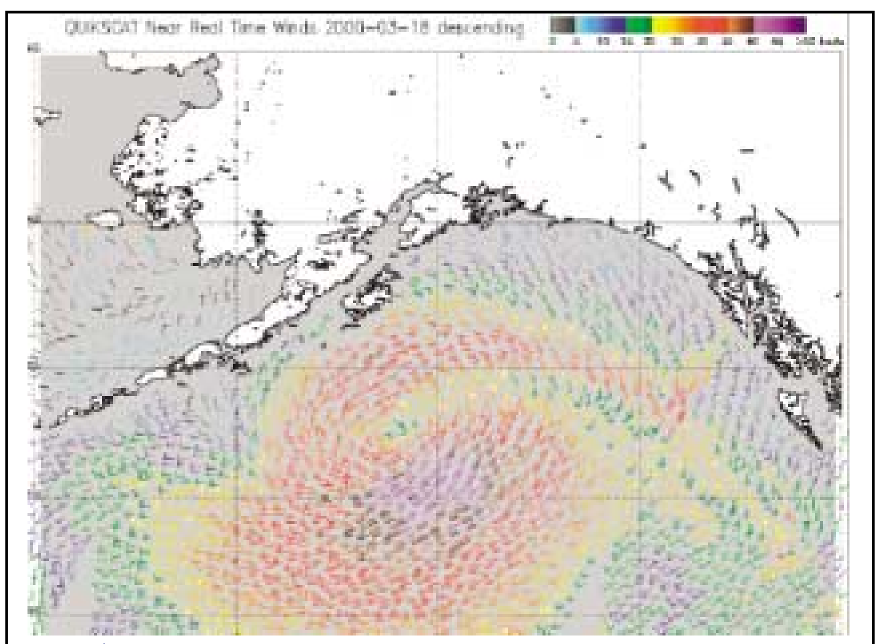


Figure 4. *Operational ocean surface vector winds from Quikscat/Seawinds.*

dialogue with potential satellite collaborators, ocean modelers, and in situ measurement programs. Concurrent investment in the education of users and scientists is an effort to build, sustain and improve the future of operational satellite oceanography. ■

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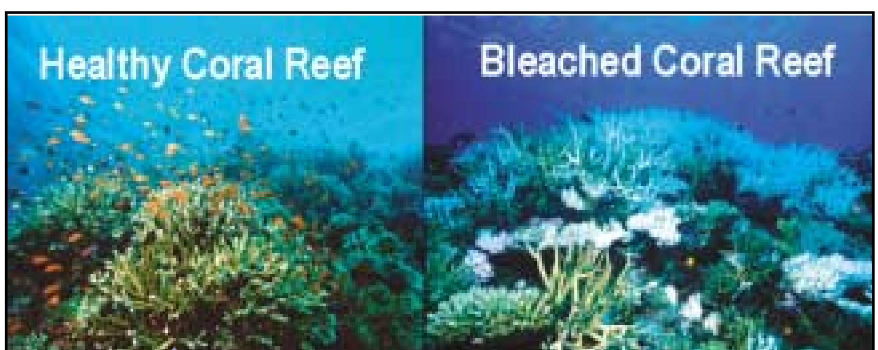

Figure 6. *NOAA's Coral Reef Watch initiative seeks to fully utilize space-based sea surface temperature observations to monitor for early indications of coral reef bleaching.*

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Mapping Ice Covered Waters from Space

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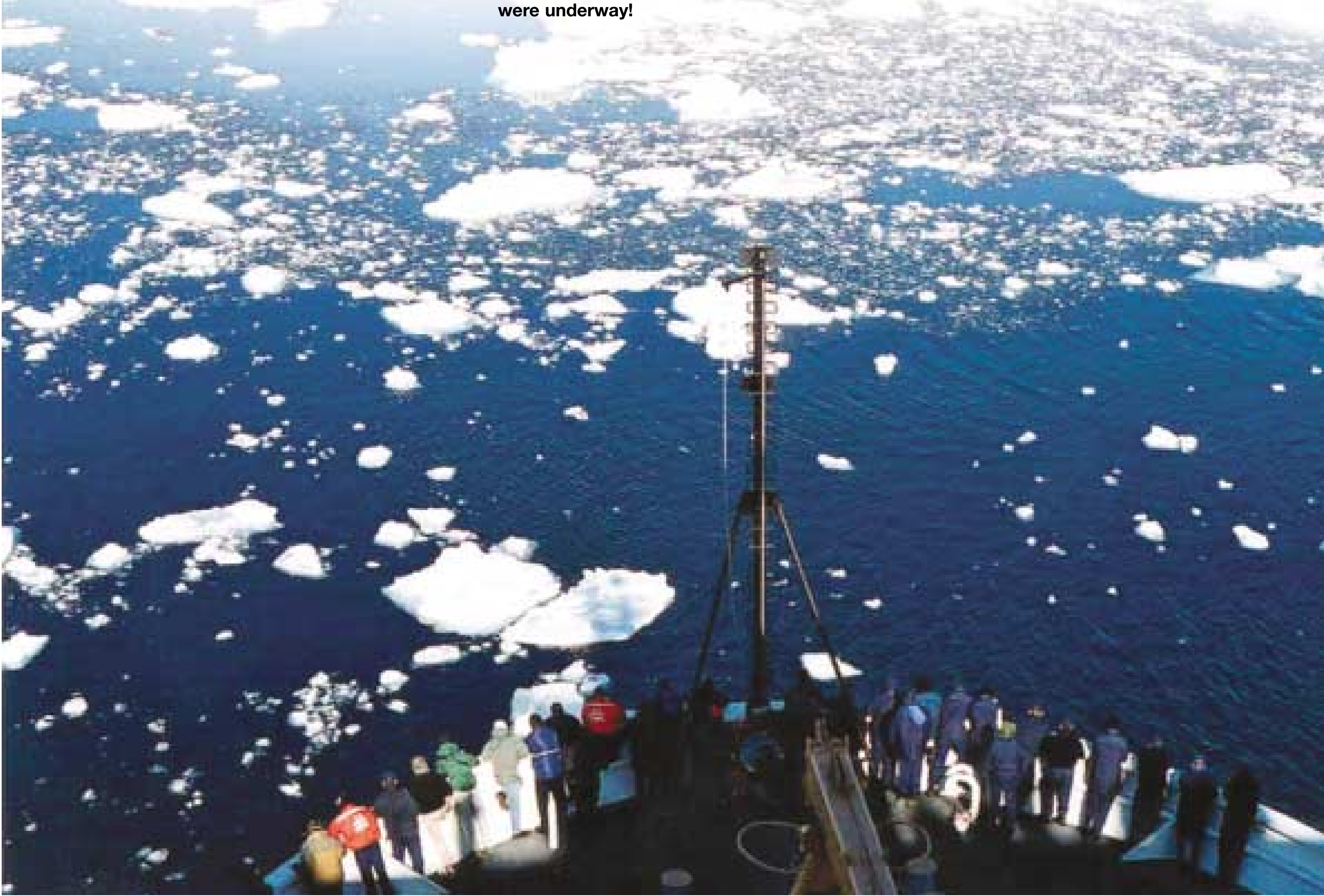
Under a leaden April Arctic sky, the United States Coast Guard Cutter Healy left the swell of the southern Labrador Sea and entered the Arctic ice pack for the first time, settling in as if she had finally found her home. The deck log notes that at about 4 pm on the 4th April 2000, the ship's captain, Bob Garrett, assumed both the deck and the con for the momentous occasion (Figure 1). The ship entered the ice at 510 33.0" N, 540 33.3" W. The ice trials of the newest U.S. icebreaker were underway!



Aboard for the trip were two expert ice analysts (Figure 2), Jeff Andrews from the U.S. National Ice Center (NIC), and Roger Provost from the Canadian Ice Service (CIS). In addition to local helicopter ice reconnaissance flights, both would count on ice information supplied through a complex infrastructure of satellites, ground processing facilities, analysis centers and communications links in order to understand and map the ice situation around them.

Like the Healy (Figure 3), ships operating in and near the Arctic and Antarctic ice packs rely heavily on products received from several national ice centers. Operational ice services from more than a dozen nations routinely issue ice and iceberg bulletins, warnings, analysis charts, and forecasts to support safe navigation in ice-affected waters. In addition, these ice analysis products are finding increasing use as a record of ice conditions to support climate change studies.

The major ice charting nations of the Arctic work in remarkably similar manners, but with differences in their geographic regions of interest, user base, and analysis data sets. Most centers now rely heavily on satellite image data as their primary data source, supplemented by airborne reconnaissance (visual or with imaging radar), ship reports, and meteorological inputs. Ice is highly dynamic and requires frequent and timely data sources for accurate charting. Each operational ice centre has invested in the infrastructure to receive, analyze and disseminate large volumes of data in near real-time. Virtually all data are now processed in digital form and geographic information systems are used to create and disseminate products.

Satellite Data Sources

Visible and thermal imagery from NOAA's Advanced Very High Resolution Radiometer (AVHRR) sensor, originally developed for meteorological applications but well suited to ice monitoring, has

Figure 2. *From left to right, Jeff Andrews (NIC), Terry Tucker (Cold Regions Research and Engineering Laboratory) and Roger Provost (CIS) investigate on ice conditions near the Healy's bow.*

Figure 1. *Ice at last! A view from the USCGC Healy as the new U.S. Coast Guard icebreaker enters the Arctic ice pack for the first time. (April 4,2000.). Photo courtesy Jeff Andrews.*

Manore, Ciaran and Roger drill.

been a long-standing workhorse for many ice centers because of its ready availability and frequent coverage. In addition, the thermal channels permit imaging of ice and interpretation of its thickness even in periods of polar darkness. Its 1 km resolution permits the charting of 'strategic' ice information suitable for making general ship routing recommendations, but not for close tactical navigation. Other nations make use of equivalent meteorological satellites such as Japan's GMS or Russia's Meteor systems. The U.S. NIC also makes extensive use of the Operational Linescan System (OLS) from the Defense Meteorological Satellite Program (DMSP) satellites, which provide 0.5 km visible and thermal imagery.

Of course, the main limitation of optical systems is their susceptibility to cloud cover. The part of the ice pack of greatest interest to ship traffic - the area near the ice edge - is typically obscured by cloud or fog about 70% of the time. A humorous but insightful rule of thumb says that this figure increases to 100% if you are actually supporting a ship in the region.

Because of weather, polar darkness and the desire for higher resolution imagery, the ice services have had a strong interest in radar remote sensing since the technology emerged. As far back as the early 1970's airborne real aperture radars (SLARs) were used to map the ice pack, and in the1980's and 1990's airborne SAR (Synthetic Aperture Radar) and SLAR systems were in operational use. In 1991, the European Space Agency's ERS-1 provided the first sustained taste of satellite radar data, and in 1996, wide-swath (500 km) SAR data became available from Radarsat-1. SAR data offers the advantage of high-resolution imaging through cloud and polar darkness, and a sensitivity to the surface roughness and salinity properties of sea ice that help to distinguish different ice types (Figure 4).

> "...the main limitation of optical systems is their susceptibility to cloud cover."

Radarsat data were quickly adopted by the Canadian and U.S. ice services under national data allocations, and later by several European ice services on a commercial basis. At the Danish Meteorological Institute (DMI) and in several other cases, the purchase of satellite SAR imagery has been made possible through cost savings by reducing or eliminating aircraft reconnaissance. It is estimated that more than 10,000 scenes per year of SAR data are currently used for operational ice monitoring.

A third satellite data source used by many ice services is passive microwave imagery from the Special Sensor Microwave/Imager (SSM/I) sensor on the U.S. DMSP satellites (Figure 5). This sensor provides near daily, all-weather, multi-channel microwave radiometry over a 1,394 km swath. Automatic algorithms for the extraction of ice edge, total ice concentration and multi-year ice concentration have been developed and validated over many years. The sensor provides only coarse resolution sea ice products (12.5 km to 25 km), but is a reliable data source for regions where only basic ice edge and ice concentration information is required for strategic navigation decisions, such as Antarctica.

Analysis

Most ice services take a similar approach to data analysis and produce sim-

Figure 3. *USCGS Healy in "spider" mode, configured for on-ice science in Baffin Bay.*

Canadian Space Agency Ad

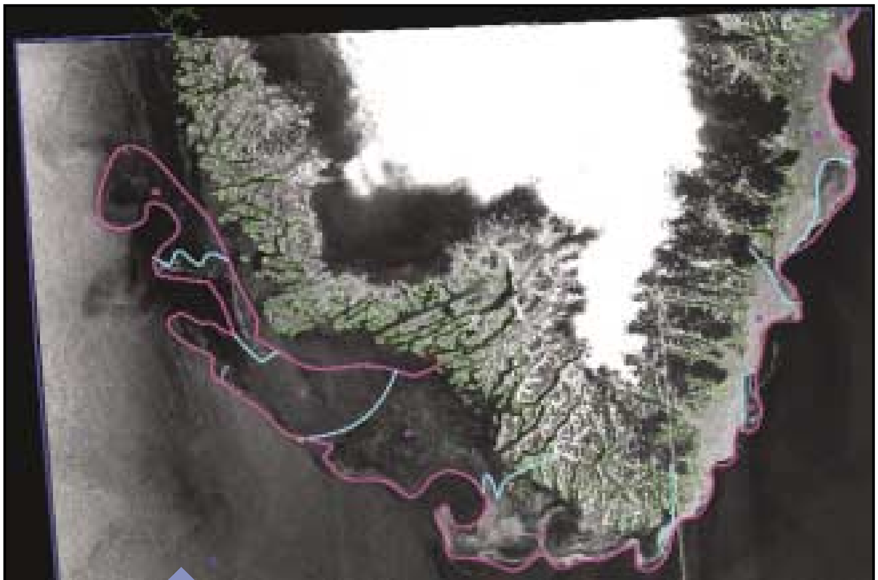


Figure 4. *The Danish Meteorological Institute (DMI) produces ice charts in the waters around Greenland. Here, Radarsat imagery is used to meet the challenge of mapping low concentrations of thick multi-year ice in the Cape Farewell region. Radarsat imagery © CSA 2000.*

ilar classes of products. Imagery from different sources are combined in a “manual data assimilation” process where the most recent and highest resolution images are analyzed first, then a progression is made through all available data. Experienced ice analysts are able to extract ice concentration, ice type (a proxy for ice thickness) and ice topography from the satellite images based on the tone, texture and spatial context of the ice features. Accurate information extraction requires an understanding of ice forms, remote sensing signatures and current meteorological conditions, as well as the historic patterns of ice in a specific region. Ship reports and visual observations are used to validate the image interpretations.

> “Experienced ice analysts are able to extract ice concentration, ice type (a proxy for ice thickness) and ice topography from the satellite images based on the tone, texture and spatial context of the ice features.”

The analysis is performed through visual interpretation by the ice analyst in a digital image display using vector drawing tools. The resulting charts are then further processed in a GIS (Geographic Information System) for electronic or fax distribution. The volumes of data analyzed by each ice service varies from a few images per week to more than 8 GB of imagery per day in the case of the NIC. Analysis systems must be sized appropriately to ingest, geocode and enhance this data, and there must be sufficient human resources to view, assimilate and analyze the imagery to produce accurate ice information. Expert-system approaches to automate the analysis process are currently being investigated in order to reduce the current labor-intensive methods.

Products

The range of products issued by the different ice services reflects their mandates and user base, but with a common goal of providing information to support safe navigation in ice. In the U.S., the NIC produces weekly global sea ice charts covering the Arctic, Antarctic and Great Lakes at region-

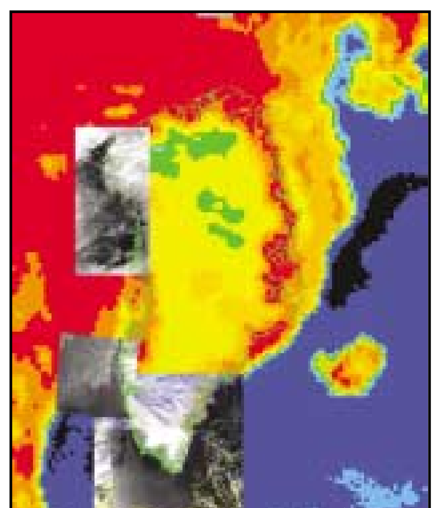


Figure 5. *In the Danish Meteorological Institute's (DMI’s) SIKU ice analysis and GIS system, an automated ice concentration product from the passive microwave Special Sensor Microwave/Imager (SSM/I) is mosaicked with visible, infrared and SAR imagery prior to conducting an ice analysis. Radarsat imagery © CSA 2000.*

al mapping scales. Operating under sponsorship of NOAA, and the U.S. Navy and Coast Guard, the NIC makes its ice charts freely available over the Internet (http://www.natice.noaa.gov) to a wide range of international mariners. Most other ice services fulfill mandates for ice information in their own national waters and operate as a public service or on a product subscription basis.

The primary ice service product is an ice chart of current or forecast ice conditions (Figure 6). Charts normally make use of the World Meteorological Organization (WMO) terminology and 'egg code' symbol to represent ice information. These charts are produced at various scales and levels of detail depending on the region, season, and available source data. Other products include the images themselves, text bulletins and warnings, seasonal outlooks, specialized ice analysis to support specific vessels (e.g. Healy ice trials, science expeditions, etc.) and long-term compilations of ice data for the climatological record (Figure 7). More specialized products may include ship route recommendations, or warnings of specific phenomena such as the breakup of landfast ice in the Arctic spring.

> "An emerging data source for ice monitoring is satellite scatterometery from sensors aboard ERS-2 and Seawinds."

Future Directions

Joining resources under the International Ice Charting Working Group (see *Backscatter*, Fall 2000, pp 12-13), the ice charting nations are working collaboratively to address issues of common operational interest. These include access to reliable and affordable data sets, technology and training, and joint research and development.

In an example of cooperative research, CIS, NIC and DMI are working together to validate and further develop an intelligent ice classification system. The future multi-channel SAR systems (Envisat, ALOS, Radarsat-2) are expected to improve the quality of ice information in the imagery but with the requirement to handle increased data volumes and to develop new analysis techniques, including the use of multi-polarization and fully-polarimetric data. The operational centers look forward to a con-

stellation of SAR satellites, which will permit better spatial and temporal coverage, as well as provide operational redundancy in the event of system failure.

An emerging data source for ice monitoring is satellite scatterometery from sensors aboard ERS-2 and Seawinds. Techniques have been successfully demonstrated to provide all weather imaging capability at effective resolutions varying from 5 km to 10 km, depending on the degree of post-processing. A Seawinds Quikscat ice product is now being routinely generated and is under operational evaluation by the NIC. Future sensors that will be of interest to the operational ice services include the Eumetsat METOP-1 (scatterom-

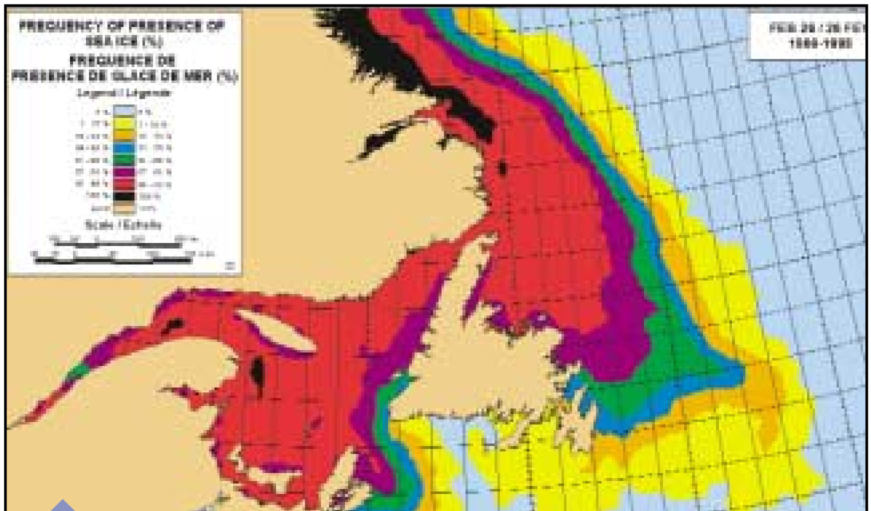


Figure 7. The history of ice conditions captured in the record of ice charts is of increasing interest for climate change studies. This product summarizes the frequency of ice occurring in late February on the East Coast of Canada based on an archive of 29 years of charts (1969-1998) from the Canadian Ice Service (CIS).

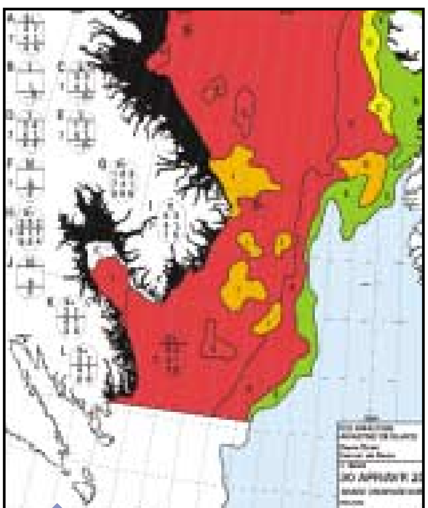


Figure 6. *A Canadian Ice Service (CIS) ice chart, prepared as an aide to navigation for the USCGC Healy. Imagery was received at CIS in Ottawa in near real-time, analyzed by an experienced ice analyst, and the resulting ice chart sent via Inmarsat to the Healy within six hours of image acquisition. CIS ice charts are available online at http://www.cis.ec.gc.ca/*

eter, optical and thermal) and the European Space Agency's Cryosat (altimeter).

The ice centers will continue to work towards developing automatic or semi-automatic methods to assist human interpreters in producing accurate and timely sea ice charts (Figure 8). The Healy and its crew will prove a valuable collaborator in this effort, collecting surface truth data to validate algorithm output. Next fall, scientists from Canada, Denmark and the U.S. will cruise the seas north of Svalbard aboard the Healy, measuring ice properties with surface-based instruments as European, Canadian and U.S. satellites fly overhead to acquire images.

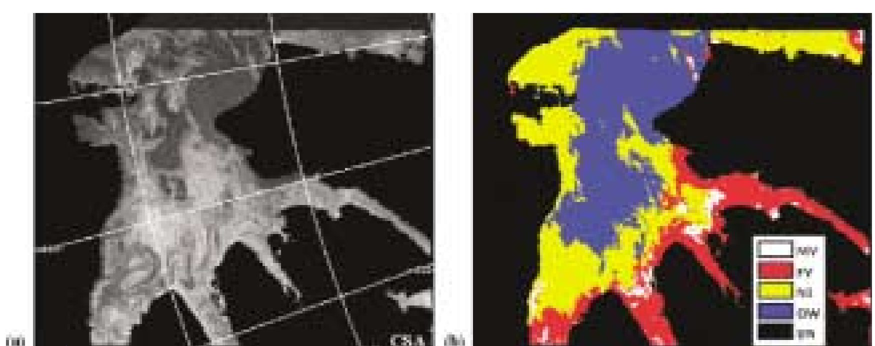


Figure 8. *The ice centers are looking to employ artificial intelligence techniques to map SAR sea ice scenes automatically. In this example, a Radarsat image has been classified into four sea ice types as shown in the legend. Radarsat imagery © CSA 2000.*

A major challenge ahead will be continued acquisition of data, as space agencies become increasingly commercially oriented. However, with continued international cooperation between the ice centers of the Northern Hemisphere, the future looks bright for continued improvements in accuracy, resolution and timeliness of operational sea ice charts produced from spaced-based sensors. ■

Mapping Floods in France

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In 1999-2000, ESA, CNES and the French Civil Defence Agency agreed to cooperatively assess the contribution of space-based remote sensing techniques to effective disaster management in an operational context. The agreement was a precursor to the International Charter on Space and Major Disasters. A demonstrator was built for flood plain monitoring and management over a test site in the Northern part of the French Meuse basin.

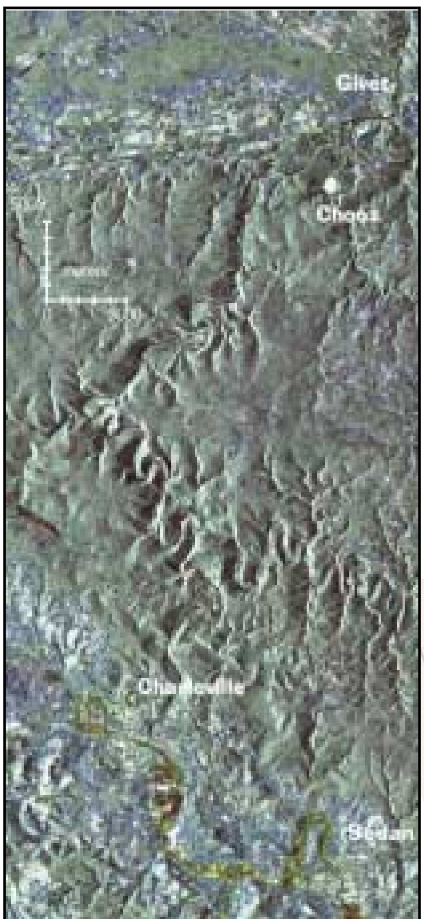


Figure 1. Location of the study area.. Color composite of monthly merged SAR images - January, February and March, in red, green and blue respectively.

The work exploited an ERS SAR time series in synergy with very high resolution optical Ikonos data. Thanks to its all weather capabilities and the specific three day acquisition mode operated during the flood events under scrutiny, ERS SAR has the potential to be used for flood management. However, it has not been investigated often.

Compared with earlier studies, this project took in account two flood events; namely, those of 1993/94 and 1995, which exceeded the estimated 100 year flow and which are comparable to the dramatic 1926 flood.

Since part of the ERS data were acquired with a baseline suitable for interferometric processing, a first assessment of the usefulness of the coherence for flood mapping was possible. This potential of ERS SAR has rarely been analyzed for the flood theme while it is now well established for landslides, earthquake analysis and more recently for wind damage assessment to forests.

Test Site and Data

The study was carried out over the Northern part of the French Meuse Basin, between the towns of Givet and Sedan. This area is the most vulnerable part of the Meuse basin in France and

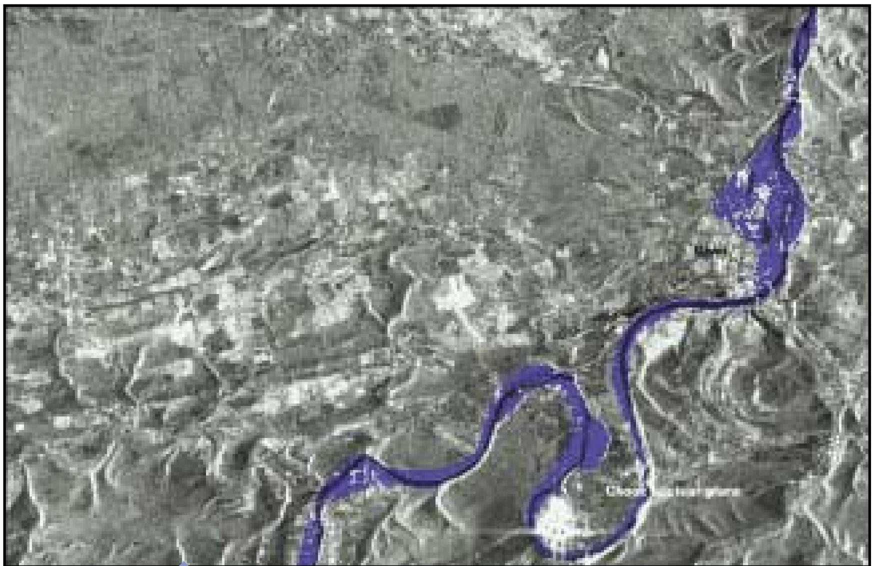


Figure 2. *Maximal extend of the 1993/94 and 1995 events - northern part of the Meuse valley.*

accounts for one third of its surface. Two sub-areas may be further distinguished, the plain of the Meuse, and the Ardennes course, where the river is surrounded by steep hills (Figure 1).

The data set consisted of 18 ERS descending images and an Ikonos scene taken in both panchromatic and multispectral mode. Sixteen ERS SAR images covered the retreat of the 1993/94 flood, with the first acquisition three days after the peak flow. The two remaining images covered the 1995 flood.

The ERS data were co-registered, then merged following a multi-temporal approach in order to produce a reference SAR product. A SAR sharpened image with a 48 look equivalent, resulting from the merging of 16 images, and monthly fused products were generated (Figure 1). Some of the ERS data were in SLC format which allowed for derivation of interferometric products.

The Ikonos data were acquired in May 1999, both in panchromatic and multispectral mode, with a spatial resolution of 1 m and 4 m respectively. A color composite pan-sharpened product was generated. The SAR reference image was used during the co-registration phase with the Ikonos data.

Flood Extent

Before mapping the extent of the flood, we identified permanent water bodies such as lakes, dams, and the Meuse river. Extraction of the flood boundaries was performed on amplitude data using a segmentation technique. This operation was performed on the 16 images covering the 1993/94 event, as well as on one image from the 1995 event. The ability of coherence products to distinguish targets with low backscattering, such as roads, railways and surrounding inundated surfaces, which are locally confused on the SAR amplitude image, was assessed. On the coherence image, these targets are well distinguished since the non inundated roads present high coherence values whereas inundated areas are characterized by very low ones.

On a few images, extraction of inundated areas was locally perturbed by the roughness of water surface due to windy weather during acquisition. These limitations of the SAR data could be eliminated in the future by using a longer wavelength less sensitive to the surface roughness. Therefore, based on a simple model, corrections were applied and it was possible to provide the temporal evolution of the inundated surfaces for the plain area between the towns of Sedan and Charleville-Mézière, and for the Ardennes part where the water inundated surfaces are smaller due to the hilly landscape.

Furthermore, maximal inundated surface maps were generated either for the 1993/94 event or for the two events - 1993/94 and 1995 (Figure 2). These products, derived from SAR time series, complement administrative maps of historically flooded areas, which do not integrate the

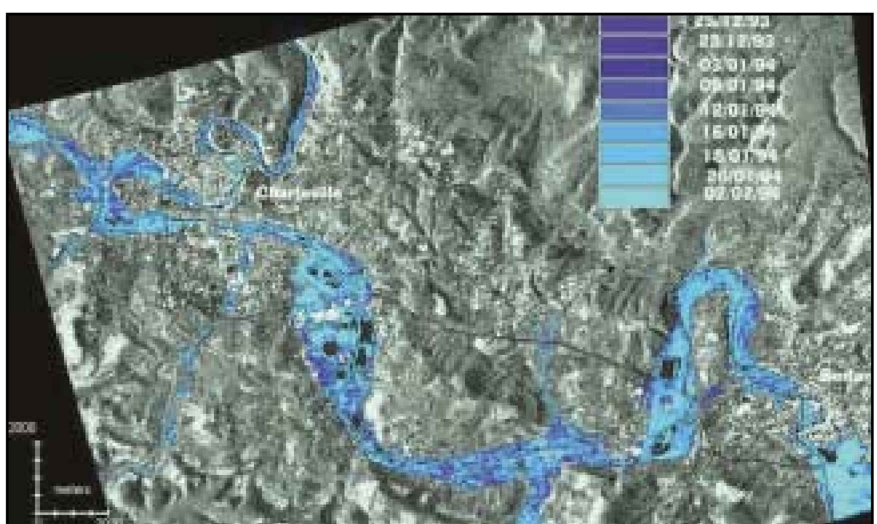


Figure 3. (a) Extent of flood retreat between 25/12/93 and 02/02/94 for the Sedan / Charleville sector. (b) Frequency of inundation based on the 1993/94 event, for the same area. This type of analysis allows for visualization of retreating waters.

latest events. In addition, this information is very suitable for flood vulnerability analysis and zoning, during the administrative process of designing risk maps. These SAR derived products will also be used as a reference for future events and for on-going activities. In this case, they represent the possible evolution of the flood, and can be used to help devise future civil engineering works such as dams or embankments, or modifications required to existing ones.

Analysis Based on ERS SAR Time Series

From the 16 flood maps covering an 81 day period in 1993/94, we carried out an analysis of flood frequency and flood retreat trends. The analysis spotted a new peak flow of small amplitude. Three maps corresponding to a first period of water retreat, the new crisis, and final retreat were produced (Figure 3a) using a color code to represent the latest date of inundation.

A frequency of inundation file was generated from the 16 daily flood boundaries. An initial file was prepared where the permanency of water, that is, the number of times water was present during the observing period, was indicated for each pixel affected by the flood. Then a synthetic map with four classes, each class grouping one to four observations together, was generated (Figure 3b). This map enables the viewer to pick up the most hydromorphic areas, thus making SAR data a powerful tool for the characterization of wetlands.

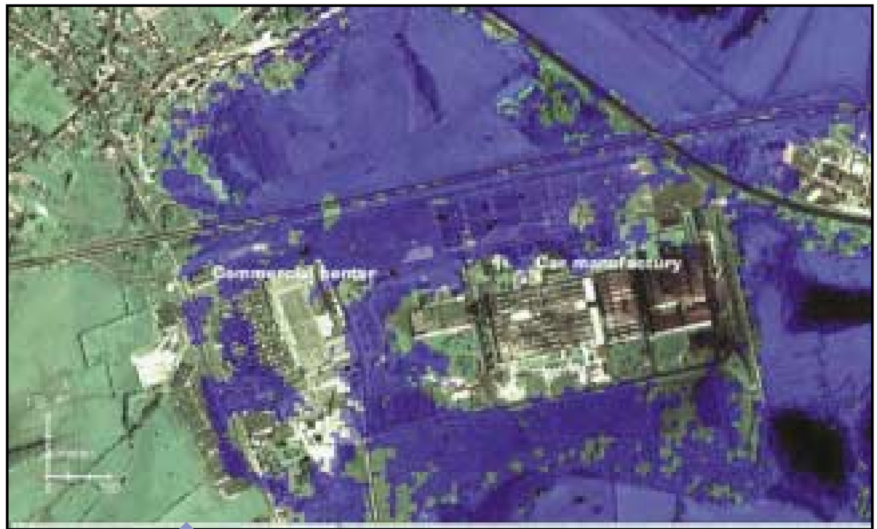
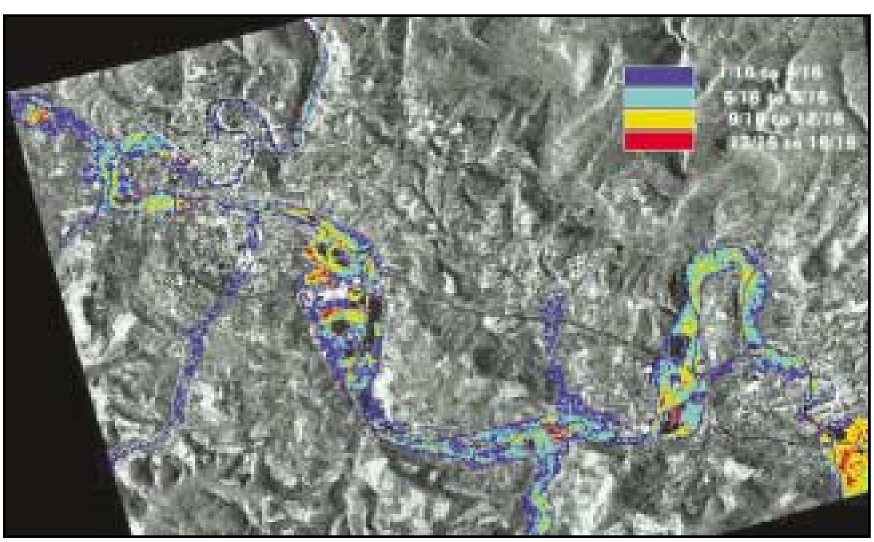


Figure 4. Damage extent and visualization based on the merging of Ikonos data and SAR derived information. Location: South Charleville, Villers-Semeuse suburb.

ERS & Ikonos Synergy

High resolution optical data, such as images from the Ikonos sensor and future sensors such as Orbview or SPOT-5, can be used together with the SAR derived products in order to manage the flood event as well as to make a rapid and accurate assessment of the damage.

One approach consists of merging the high resolution optical imagery with the SAR data (flood extent). This permits direct identification of the affected area: in this case, a car plant, a commercial centre, a hospital, and the fire brigade building (Figure 4). This type of product, equivalent to a 1:5,000 or 1:10,000 map, is very useful for the Civil Defence during prevention and crisis phases. It can also be used to spot future civil engineering needs, such as future dams, embankments, or modifications to existing ones. This type of product is complementary to aerial photographs, which are hampered by adverse weather conditions and by the very large extent of a plain inundation (Figure 5). During post crisis analysis, the combination of the high resolution Ikonos image and the SAR-derived flood frequency product is also helpful for flood vulnerability analysis and mapping.



Another approach involves merging land use/land cover layers derived from high resolution data with the flood extent derived from the ERS SAR images (Figure 6). This information relating to the affected land cover themes is of great importance to the public agencies in charge of naturals hazards and civil security, and to insurance companies. It is also helpful at different stages of a flood crisis. During a flood, based on a reference event, it allows an anticipation of safety measures concerning population and emergency material, with a definition of the main assets. At the end of the crisis, the obtained product allows for precise impact assessment. It is possible to

Figure 5. a & b (see page 23 for b). Oblical photographs of the Charleville Mézière January F95 flood, Saint Julien and Pierre suburbs, acquired from a helicopter (Courtesy of the Navigation Service).

distinguish the low value damage, such as parking, prairies and crop lands, from the economically high values ones, such as individual houses and industrial areas (which in this case cover respectively 33 and 37 ha). This is valuable information for estimating initial financial support as well as for issuing the official "natural catastrophes" decree. During post crisis analysis, this information is valuable for monitoring land cover change within sensitive areas, as well as for updating vulnerability maps.

Conclusion

The project demonstrated an effective contribution of Earth observation data to a flood information system on the Meuse basin. A set of maps has been generated, which will be included in an operational GIS presently under development at the Regional Security Service. The first ones correspond to a "maximal flood extent map" and to "flood dynamics" and "flood frequency" maps derived from ERS time-series acquired within a three day revisit mode. In an operational context, the combination of SAR-derived information with high resolution optical data would be used to visualize flooded areas and would support decision making. These products provide valuable information for definition of stakes, for damage assessment as well as for monitoring of land cover change and updating vulnerability in sensitive areas.

These results also indicate the limitations of current radar systems, and call for definition of future missions, providing daily revisit as a minimum for all participants involved in flood monitoring, and a lower sensibility of water surface roughness. ■

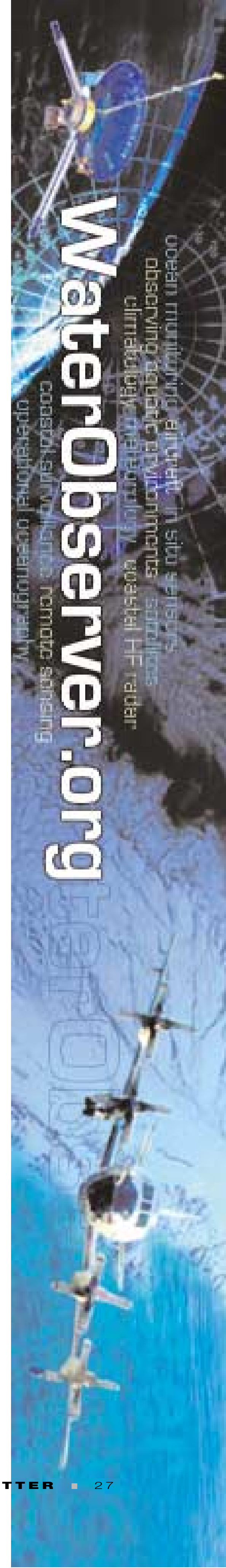
> "These results also indicate the limitations of current radar systems, and call for definition of future missions, providing daily revisit as a minimum...."

Acknowledgments

This work was carried out under contract with the European Space Agency. The authors would like to thank K. Fellah for the production of coherence data as well as P.Y. Valantin of the Service of the Navigation, Nancy, who provided oblique aerial photographs acquired during the 1995 flood in collaboration with the Rhin Meuse Water Agency.

Figure 6. Damage assessment of the 1993/94 flood based on exploitation of the land use/cover map derived from Ikonos data and the flood boundaries obtained from ERS SAR data. - Saint Julien and Pierre suburb of Charleville Mézières.

the Web portal for the marine environmental-information community



Ocean Color Spectrum

news from the international ocean color community

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France

Florence Lahet of the Laboratoire Régional de Télédétection in French Guiana, a laboratory of the Institut de Recherche pour le Développement (IRD), writes: “An HRPT receiving station has been operational since 1998 at the IRD (formerly ORSTOM) research center of Cayenne (French Guiana). The station is part of the SEASnet (Survey of Environment Assisted by Satellites) network developed by IRD. This network includes four stations (French Guiana, La Reunion, New Caledonia, Canary islands)."

The general aim of these programs is to provide the scientific concepts and the tools required for an integrated management of the Amazonian coastal zone. At Cayenne, in particular, NOAA-AVHRR data are received and processed every day to determine sea surface temperature fields and turbidity maps. The influence of the Amazon River, the world’s largest river in terms of freshwater discharge, is examined in the frame of the French-Brazilian program ECOLAB (Ecossistemas costeiros amazônicos) and of the French program PNEC (Programme National Environnement Côtier).

We presently use SPOT and AVHRR data, and Seawifs data will be available in a few weeks.

Japan

(1) Sonoyo Mukai (mukai@im.kindai.ac.jp) and Itaru Sano (sano@im.kindai.ac.jp) of Kinki University, Japan, are collaborating on a research project entitled “Aerosol retrieval for/from ocean color sensors”. They describe their research this way:

“Aerosol characteristics on a global scale are strongly needed for better understanding of Earth's radiation budget and effective analysis of satellite data, especially ocean color data. We intend to propose a procedure for retrieval of aerosol properties such as optical thickness (t), Angstrom exponent (a) and complex refractive index (m) over the ocean, over the land, and over the coastal zone through a combination of radiance and polarization.

Most ocean color sensors are generally designed to monitor atmospheric aerosols with near infrared (NIR) data. t and a over the ocean have been retrieved by using radiance data in the NIR region based on a two-channel algorithm. We suggest that polarization information is available to estimate the values of m, and polarized radiance is very useful to retrieve aerosol characteristics especially over the land and the coastal zone. It is well-known that atmospheric light over the coastal zone is strongly contaminated by the oceanic signal. We can therefore say that aerosol retrieval over the coastal zone is an important subject in ocean physics as well as in the atmospheric field. We note that aerosol retrieval is greatly improved with polarization information.

Our algorithms for aerosol retrieval are examined with Adeos/Polder data. Polder was one of eight sensors onboard the Japanese Adeos satellite launched on 17 August 1996. The obtained global distribution of aerosol properties are compared with data from other sensors and are validated by ground measurements, such as Aeronet. Our Aeronet/CIMEL - sunphotometer (#103) is set at the fishery institute in Shirahama by

the Pacific Ocean, where oceanic and atmospheric measurements have been compiled.

We have been conducting atmospheric sunphotometry and polarimetry with the multi-spectral polarimeter (PSR1000) over the ocean and coastal zone since 1996."

(2) It may not be ocean "color", but Backscatter also features articles about synthetic aperture radar in the marine realm. In that regard, Ken Ishii (kenmaru@affrc.go.jp) of the National Research Institute of Fisheries Engineeering, Japan, says that a recent paper in the Bulletin of NRIFE (February 2001) describes a way to observe fish distributions from surface to depth. The paper is "Using Synthetic Aperture Radar Data for Information Ensuring of Fisheries Oceanography - Present and Perspective" by V. Zabavnikov (Russia) and K. Ishii.

The United Kingdom, and Belize

Rob Nunny of Ambios Ltd. (robnunny@ambios.net) provided a description of a current research program, "Monitoring of Water Quality in the Belizean coastal zone using satellite ocean colour imagery." His associates on the project are Samantha Lavender (Institute of Marine Studies, University of Plymouth, U.K.), Gerald Moore (Plymouth Marine Labs, U.K.), Delia Tillett (WRIScS Project, Belize) and Jon Cooke (Raleigh International).

"The Watershed Reef Interconnectivity Scientific Study (WRIScS) is a four year EU funded project that has been concerned with the impacts of soil erosion on reef turbidity regimes. In its final year, the project has teamed up with ocean optics experts from Plymouth institutions, with the objective of exploring the possibilities of using Seawifs imagery as a practical tool for monitoring coastal water quality in developing countries.

The area is optically shallow (less than 25 metres depth) and therefore seabed effects must be taken into account - the research is primarily concerned with attempting to identify and remove seabed interference / effects within the image, in order that water colour information can be routinely derived from satellite data.

The seabed is being characterised and mapped on a range of scales through acoustic (RoxAnn), diver (SCUBA) and optical techniques (e.g. underwater digital photography). PRR (Profiling Reflectance Radiometer) profiles are also being routinely collected. This <sic> data, together with time-series observations of water quality (e.g. CTTD and Secchi observations, and from filtration and spectrophotometric analyses of bottle samples), are being stored within a Geographical Information System (GIS), together with existing relevant data. This <sic> *in-situ* data will be used to explore methods for correcting the satellite ocean colour (primarily Seawifs) imagery so that data on, for example, Suspended Particulate Matter (SPM) can be derived.

In 2001, expeditions are being carried out from March to May and July to September, which are the dry and rainy seasons respectively. Fieldwork is being undertaken by volunteer diver teams from Raleigh International, under the guidance of the WRIScS team. The fieldwork locations are in the north and south of the Belize coastal zone."

The United States

(1) John H. Paul of the University of South Florida (jpaul@seas.marine.usf.edu) will be in the Gulf of Mexico on the University of Miami's fairly new twin-hulled R/V F.G. Walton Smith, from 14 - 27 July. Paul's research team will be investigating coastal plumes located with the aid of satellite imagery from Frank Muller-Karger's remote-sensing laboratory at USF. Paul and his colleagues will measure new production, RuBisCO gene expression, and nutrients, as well as building libraries of RuBisCO genes.

Also from USF: Chuanmin Hu indicated that his recent paper should be of interest to many Seawifs data users. The paper is Hu, C., Carder, K.L., and F.E. Muller-Karger, How precise are SeaWiFS ocean color estimates? Implications of digitization-noise

errors, Remote Sensing of Environment, 76, 239-249, 2001.

(2) Researchers at Goddard Space Flight Center (Antony K. Liu, Yunhe Zhao, Wayne E. Esaias) and the University of New Hampshire (Janet W. Campbell and Timothy Moore) are examining Seawifs and Modis observations of the same Atlantic Ocean region, separated by only 67 minutes, using wavelet analysis. Tracking of subtle changes in that time period indicates the mixed layer drift and direction. A paper describing this research is in the final stages of preparation. ■

Acoustical Oceanography and Satellite Remote Sensing

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At first glance, underwater acoustics, satellite remote sensing and oceanographic modelling may seem to have little in common. However, in recent years it has become clear that assimilation of remotely-sensed data into ocean models may significantly enhance predictions of the underwater acoustical environment.

Knowledge of underwater acoustical propagation conditions, and the structure of the ambient noise field, is of interest to oceanographers, the military and environmentalists.

Acoustical oceanography and satellite remote sensing was the theme of a special session of the Acoustical Society of America (ASA) meeting held at Newport Beach, California in December, 2000. The session brought together researchers in underwater acoustics, physical oceanography and remote sensing to examine the growing synergy between these three fields. The session, chaired by the author, covered subjects ranging from techniques to assimilate remotely-sensed data into oceanographic models to detection and modelling of internal waves.

Oceanographic Modelling

The session began with a presentation by J. Bobanovic (Dalhousie University, Canada) on estimating water density structure from in situ and remotely-sensed ocean data. The modelling is based on an implementation of the Princeton Ocean Model (POM), a three-dimensional non-linear prognostic model that has been used extensively for coastal studies.

To take advantage of the information content of remotely sensed data, methods to assimilate the surface data into the oceanographic model are being developed. The approach is to first create high spatial resolution fields of seasonally dependent temperature and salinity profiles. The fields, which have a horizontal resolution of approximately 2 km and a vertical resolution of 5 to 10 m, are produced by assimilating monthly climatology of temperature and salinity into the POM. The monthly climatology is based on archival water column profiles from the Department of Fisheries and Oceans, Canada, and Advanced Very High Resolution Radiometer (AVHRR) sea surface temperature (SST) data from NASA's Jet Propulsion Laboratory. The result is a set of seasonal fields that are consist nt with the historical data, and dynamical constraints imposed by the POM.

Figure 1 shows a comparison of the average SST over the Scotian Shelf for week 19, based on twenty years of AVHRR data, to SST generated with the POM based on the historical observations. The open boundary conditions for the Scotian Shelf

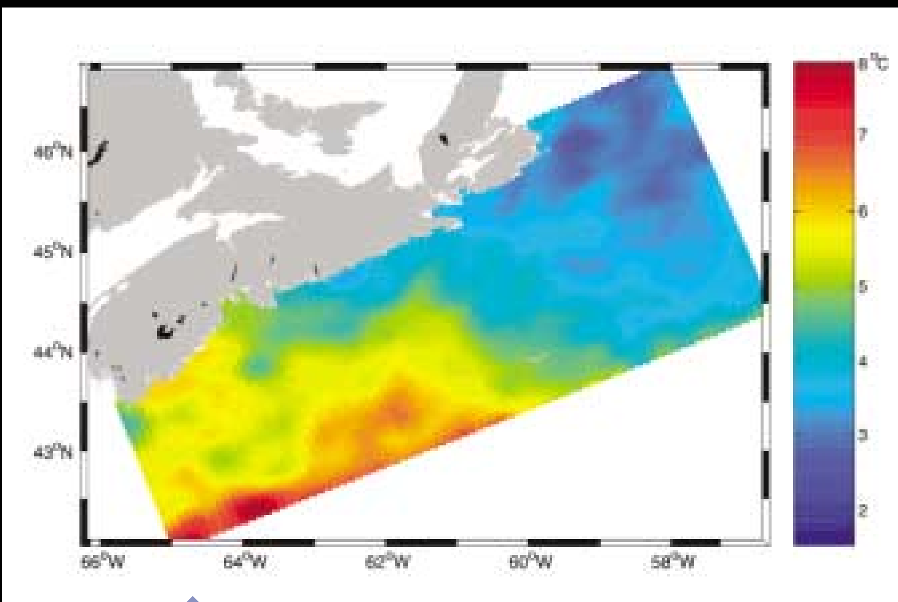
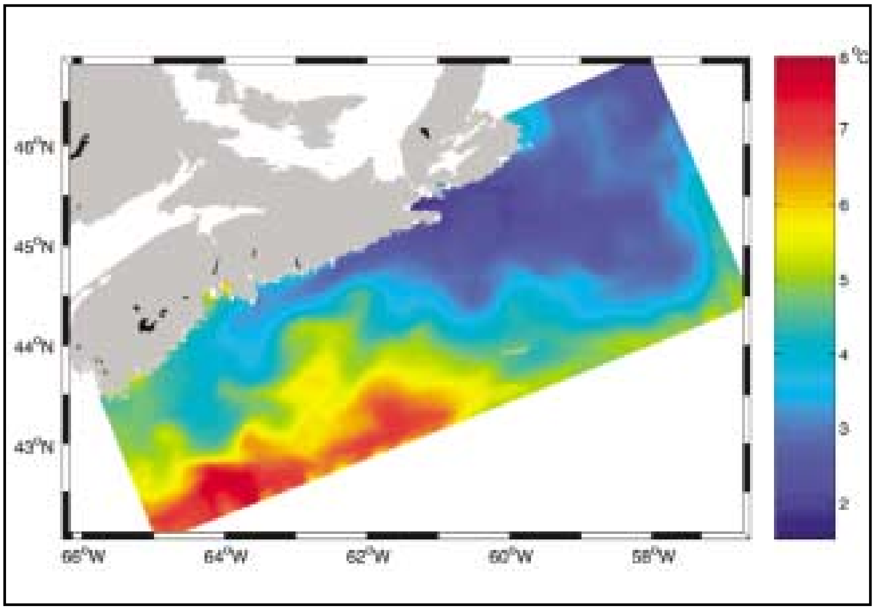


Figure 1. *(a) Average SST over the Scotian Shelf for week 19, based on twenty years of AVHRR data (seven day average). (b) model-predicted SST for May (ten day average).*



are provided by nesting it within a lower resolution POM (1/16 degree) of the Gulf of Saint Lawrence and the Scotian Shelf that currently provides operational forecasts (www.dal.ca/~dalcoast) for the region. The objective of this work over the next couple of years is to develop practical schemes for assimilating remotely sensed ocean data such as SST, altimetry and surface currents into the model.

C. Barron (Naval Research Laboratory, Stennis Space Center, USA) described the U.S. Navy's Modular Ocean Data Assimilation System (MODAS), used operationally to estimate subsurface temperature and salinity fields on a global scale. Satellite observations of sea surface height from Topex/Poseidon and ERS-2, and sea surface temperature from AVHRR, are processed by the MODAS synthetic profile routine to generate subsurface temperature and salinity fields. They are consistent with the surface observations and climatology. Any available in situ measurements can be assimilated as well, resulting in increased accuracy for local predictions. A sound speed field calculated from the temperature and salinity estimates provides the basis for acoustical applications such as predicting the performance of navy sonar. MODAS also includes a fully relocatable version of the Princeton Ocean Model. The POM obtains boundary conditions from a global implementation of the Navy Coastal Ocean Model, which in turn assimilates

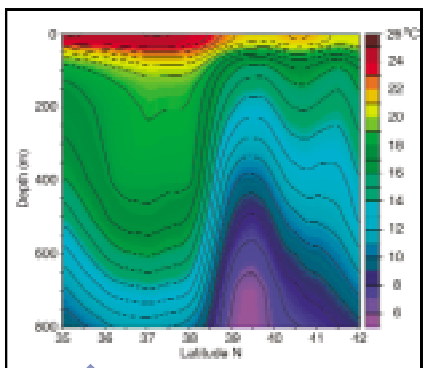
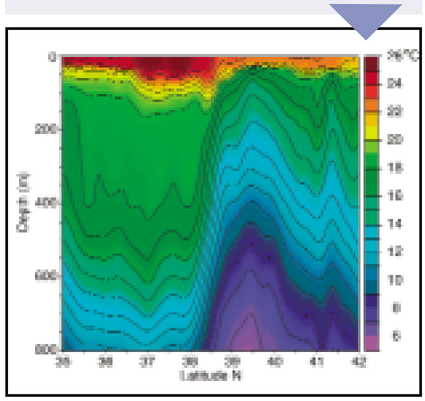


Figure 2. *Using remotely sensed SST and altimetry data, MODAS predicts the presence of a cold-core eddy in the North Atlantic (a), a result that is confirmed by an AXBT survey (b).*



remotely-sensed altimetry and surface temperature data using MODAS synthetic profiles.

Comparison of MODAS products with finely sampled water column measurements show significant improvement over profiles estimated on the basis of static climatology. For example, the 2-D temperature profiles from the North Atlantic in Figure 2 show how MODAS predicted the presence of a cold core eddy which was confirmed by a survey of air-deployed expendable bathythermographs (AXBT). Such a feature could not have been modelled on the basis of climatology alone.

Considering a much finer spatial scale, Henrik Schmidt (MIT) described progress of the MEANS (Multiscale Environmental Assessment Network Studies) program aimed at modelling the very shallow near shore region, with water depths up to only a few tens of metres. Modelling this environment is particularly challenging due to its complex dynamical nature with strong coupling between different scales. For an experiment in September and October, 2000, a local high-resolution model of Procchio Bay, Elba, was set up. The model was constrained by assimilating oceanographic data from autonomous underwater vehicles (AUVs) and current meter moorings. The local model was nested within a regional Ligurian Sea model and a basin-scale circulation model which were both constrained by surface ship measurements and satellite remote sensing data. The oceanographic models are implementations of the Harvard Ocean Model. The work is aimed at predicting the acoustical environment of the littoral region in order to improve the performance of AUVs which rely on sonar for navigation and sensing.

Internal Waves

Internal waves are slowly propagating sub-surface oscillations of the stratified water column. They are frequently observed at shelf edges in the summer as a result of tidal flow over the bottom topography. The displacement of the thermocline caused by internal waves can have a great impact on the propagation of underwater sound in the surface duct and can significantly affect the performance of sonar systems.

J. Small (DERA Winfrith, U.K.) reported on remote sensing of internal waves using space-based synthetic aperture radar (SAR) imagery and on efforts to model their SAR backscatter signature. Figure 3 shows a complex internal wave field over the Malin shelf edge north-west of the U.K., as seen in ERS-1 SAR imagery. Coincident and near-coincident in situ surface current measurements were used to infer the two-

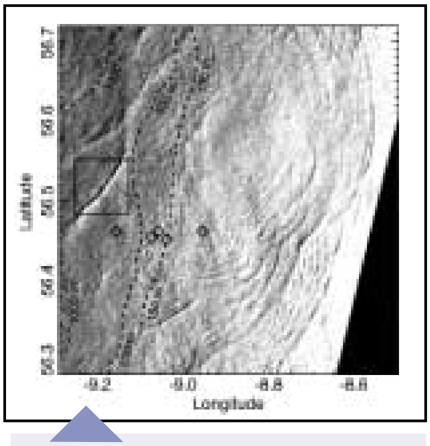
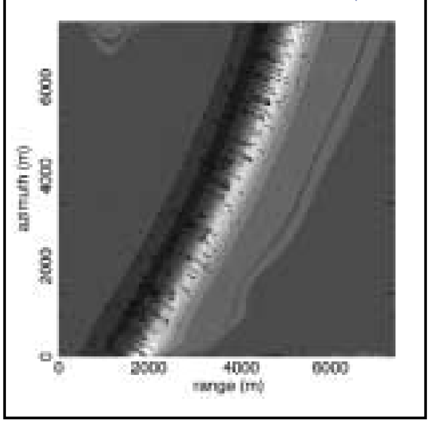


Figure 3. *ERS-1 SAR image of the Malin shelf edge, 20 August, 1995 (a), showing a complex internal wave field. Diamonds mark the positions of Acoustic Doppler Current Profilers. The box encloses an internal wave bore for which the relative backscatter was simulated (b) based on the surface currents shown as vectors in the figure. ERS-1 image © ESA, 1995.*



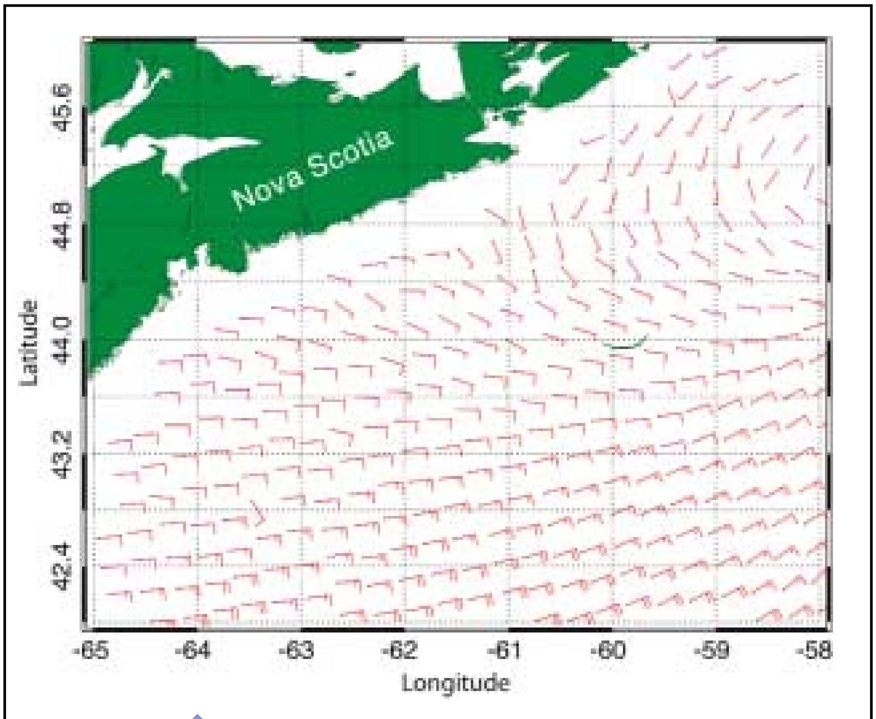


Figure 4. *Surface wind fields over the Scotian Shelf derived from NASA Quickscat data, 18 October 2000.*

dimensional surface current field in the vicinity of the high amplitude internal wave bore enclosed in the box in the SAR image. The surface current data were used with the C-band backscatter model of Lyzenga and Bennett (Environmental Research Institute of Michigan) to predict the SAR contrast between the high and low reflectivity bands of the internal wave. The observed and modeled SAR backscatter contrasts were within 30% of each other. This suggests that it may be feasible to use the remotely-sensed SAR backscatter ratio, along with estimates of the width and spacing of internal waves packets, to model internal waves. Such a capability would be extremely valuable for remote sensing of these important ocean structures and for estimating their effect on underwater acoustics.

Air-Sea Interface

Acoustical interaction in the vicinity of the air-sea interface is a complex mix of scattering by surface roughness, scattering from air bubbles and boundary interference effects. Thus the air-sea interface can have an important impact on underwater sound propagation by attenuating and redirecting acoustical energy. Since Bragg scattering of electromagnetic waves at the sea surface gives rise to the measured backscatter signature in SAR imagery, there is an intimate connection between SAR remote sensing and acoustical scattering by the sea surface.

R. Gauss (Naval Research Laboratory, Washington DC) presented work on models of surface acoustical scattering that rely on readily observable environmental quantities. The main scattering mechanisms affecting underwater sound in the air-sea interaction zone are Bragg scattering by surface roughness and scattering from air bubbles entrained in the water by breaking waves. The scattering strength of both surface and bubbles is primarily a function of wind speed. However, as the scattering from the interface is proportional to the surface wave spectral density at the Bragg wavelength (with modifications due to tilt and modulation by longer waves), a secondary environmental parameter that affects scattering strength is the sea surface wave spectrum. Additionally, the mean frequency-shift characteristics of the acoustic signals scattered from both the moving sea surface and bubble clouds depend primarily on the 2-D surface wave spectrum. The sensitivity of scattering strength and frequency shifts to remotely-sensed variables is such that it may be feasible to use remote sensing to make accurate predictions of both these acoustic quantities in near real-time over wide areas. Estimates of sea surface winds from existing SAR satellites are already adequate and 2D sea surface wave spectra have been measured successfully using airborne SAR. However, the large range-to-velocity ratio (R/V) for space-based SAR instruments makes inversion for wave spectra highly nonlinear and thus inaccurate using current techniques.

Ambient Noise

Underwater ambient noise is a major factor which limits sonar performance. Estimates of ambient noise levels are required for operational predictions of sonar detection range. Ambient noise is generated primarily by the turbulent interaction of wind with the sea surface and by shipping. The noise level at a given location also depends upon water depth, bottom type and propagation conditions since local noise is a superposition of contributions from both nearby and distant sources.

The author presented work on the estimation of underwater ambient noise with the aid of remotely-sensed wind and ships. An analysis of the sensitivity of ambient noise to wind speed showed that the accuracy of remotely-sensed surface wind using Radarsat-1 and ERS-2 SAR is adequate for ambient noise predictions in the 100 Hz to 2000 Hz band. One experiment performed in deep water north of Bermuda showed that ambient noise could be predicted to within 1 dB using surface winds from Radarsat-1. However, shallow water environments are of greater interest and pose a much greater modelling challenge. An experiment was carried out in October 2000 on the Scotian Shelf, where winds from Quickscat (Figure 4) and ship detections from Radarsat-1 are being used to model ambient noise in this shallow water environment. Ambient noise modelled using the remotely-sensed winds and ships will be compared to measurements made with aircraft deployed sonobuoys.

Summary

The work presented at this session fell into two broad categories: modelling of ocean structure with the aid of assimilated remotely-sensed data and direct interpretation of remotely-sensed surface characteristics. Since the speed of sound in water is primarily a function of water temperature (with a lesser dependence on salinity and depth) the output of oceanographic models can be readily interpreted in terms of acoustical propagation. The availability of global operational remote sensing data such as provided by the AVHRR instruments and radar altimeters has allowed ocean models to be demonstrated at scales ranging from the littoral zone to global. It was apparent from the session that much work remains to be done to fully exploit the information content of remotely sensed data. The steadily increasing coverage and resolution of remote sensing products coupled with advances in computation and modelling techniques holds tremendous potential for nowcasting and forecasting the acoustical ocean environment.

It was shown that there is good potential for estimating acoustical scattering strength at the sea surface using wind data provided by space-based SAR. Furthermore, combining remotely-sensed winds with ship detections enables the underwater ambient noise field to be estimated. However, the narrow swath widths, between 100 and 500 km, and the high cost of SAR data preclude its use operationally. Improved wind and ship detection anticipated from the next generation of polarimetric SAR satellites may translate into even better surface scatter and ambient noise estimates. For now, the inability of space-based SAR to estimate the power spectrum of surface gravity waves is an important limitation for estimation of surface acoustical scatter and low frequency ambient noise. ■

Weather Forecasting

with the aid of ocean color data

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Ocean color data have provided an unprecedented view of the changing optical properties of the ocean during the past few years (Arnone and Gould, 1999; Acker 1997). Much of this has been used to study the biology of ocean microorganisms (e.g., phytoplankton, zooplankton) and the transport of suspended particles (e.g., sediments in river discharges). However, one of its unforeseen potential applications is to help improve weather forecasting.

> “Ocean temperature influences our weather.”

Weather is strongly influenced by the exchange of heat between the atmosphere and ocean. Thus, ocean temperature influences our weather. This is particularly true in the equatorial regions with El Niño events being one of the more notable results of the atmosphere-ocean interaction. While the atmosphere can warm or cool rapidly in response to heat sources such as solar irradiance (heating), it is incapable of storing heat energy for long periods of time. The ocean, in contrast, is a very good heat reservoir and can release heat back to the atmosphere over periods of months to years. The amount of heat exchange between the atmosphere and ocean (heat flux) is primarily dictated by the temperature difference between the air and seawater.

While atmospheric models predict the surface air temperature they depend upon ocean sea surface temperature (SST) from other sources as a boundary condition. The SST significantly affects the atmospheric models. The numerical models presently being used for weather forecasting by the major weather prediction centers such as the European Centre for Medium Range Weather Forecasts (ECMWF), Fleet Numerical Meteorology and Oceanography Center (FNMOC), and the National Center for Environmental Prediction (NCEP), employ an atmosphere only component and depend upon SST from a combination of remotely-sensed (e.g., Multi-Channel SST) and in situ observations (e.g., Tropical Atmosphere Ocean and National Oceanographic Data Center moorings). Future improvements to weather forecasting are expected from the development of atmosphere-ocean coupled models, i.e. models containing both an atmosphere and ocean component that execute simultaneously and exchange information at the air-sea interface (e.g., the Coupled Ocean-Atmosphere Mesoscale Prediction System). For these models the accurate prediction of SST by the ocean model will be important. Any information such as ocean color that can be used to improve the SST from ocean models is therefore a desirable addition that merits consideration.

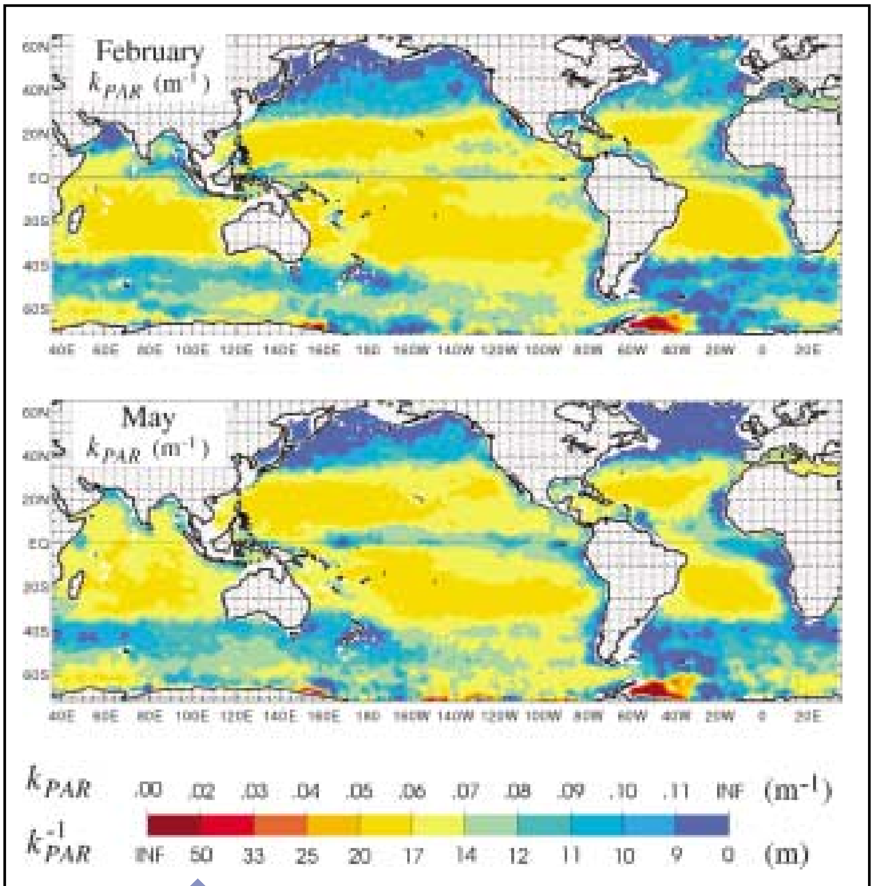

Figure 1. *Global attenuation of PAR [k(PAR)] for the middle month of the northern hemisphere winter (February) and spring (May). The corresponding optical depth [k(PAR)-1] is shown on the color bar.*

Ocean Color & Subsurface Solar Heating

Solar irradiance reaching the ocean surface and its attenuation with depth is one process that directly influences SST as it determines the amount of solar heat energy that is deposited within the ocean. The solar irradiance at the ocean surface ranges in wavelength from about 300 to 2,800 nm, and is composed of three general regions: the ultra-violet (UV) below 400 nm, the visible 400-700 nm, and the infrared (IR) above 700 nm. Approximately half of the solar irradiance occurs in the infrared, and most of this is absorbed and converted to heat within the first few centimeters of the upper ocean.

The remaining incident visible solar irradiance that penetrates below the ocean surface is predominantly in the visible and UV, and this is regulated through optical absorption by the water, phytoplankton, and suspended particles. This latter portion of the spectrum is referred to as the photosynthetically available radiation (PAR) because of its importance for biological processes. PAR is defined as the region of the optical spectrum spanning 350-700 nm, and accounts for 43-50% of the solar irradiance that reaches the sea surface. PAR comprises most of the solar irradiance that penetrates to ocean depths greater than one metre, and can reach depths greater than 100 metres.

The absorption and depth dissipation of

this heat is the quantity of interest for subsurface solar heating in an ocean model. The remaining components of the heat flux at the ocean surface (outgoing longwave radiation, latent and sensible heat flux) are locally confined to the air-sea interface and their heat/cooling contributions can be considered to be absorbed/loss within the uppermost 1 metre of the ocean.

Previously, the spatial and temporal variation of PAR and its attenuation within the global ocean was not known, thereby making it unclear as to the relative importance of solar subsurface heating on SST prediction. The latter is expected to be most important in the equatorial regions where the mixed layer (uppermost region of approximately uniform density directly beneath the surface) can become shallower than the depth of penetration of solar irradiance, thereby allowing heating to occur below the mixed layer. In ocean models that previously assumed complete absorption at the surface (or within the mixed layer) this subsurface heating would produce the largest decreases in SST. With the availability of Seawifs ocean color data, the PAR and optical attenuation in seawater can be estimated (Acker, 1997). Therefore, it now becomes possible for the first time to estimate the seasonal and spatial variation of subsurface heating throughout the global ocean, and incorporate its influence into the SST prediction of ocean models.

Optical Attenuation and SST

The optical properties change in space and time in the global ocean as is clearly observed in ocean color imagery. Seawifs diffuse attenuation coefficient at 490 nm [k(490)] is being used to estimate the near surface rate that PAR is attenuated [k(PAR)] with depth beneath the ocean surface.

We have determined monthly mean k(490) data which we have post-processed to fill in regions of missing data (Rochford et al., 2001). The resulting fields of k(490) and k(PAR) have the necessary continuity in space and time required for use by ocean models as shown by the examples for the mid-months of the four seasons (Figures 1 and 2). These fields in themselves reveal that most of the global open ocean is relatively clear [k(PAR) = 0.06 m-1] with the depth at which PAR decreases by e-1 from its surface value [the optical depth, k(PAR)-1] is greater than 14 m. Regions of much more opaque waters are seen to occur in the Arabian Sea, North Atlantic and North Pacific Oceans, the western coastal regions of Africa, and some parts of the Equatorial Ocean and Antarctic. Absorption is greater in these regions because of the dominance of phytoplankton. The large areas covered by these opaque waters can represent a sizeable heat exchange between the atmosphere and ocean, and hence have an appreciable impact on weather prediction.

We investigated the effects of using Seawifs derived k(PAR) in a global ocean model (Metzger et al., 2001) to predict global SST and MLD (Rochford et al., 2001). We compared model differences in the annual mean SST with and without subsurface heating using Seawifs k(PAR) fields (Figure 3). By neglecting subsurface heating, the annual

> “PAR comprises most of the solar irradiance that penetrates to ocean depths greater than one metre, and can reach depths greater than 100 metres.”

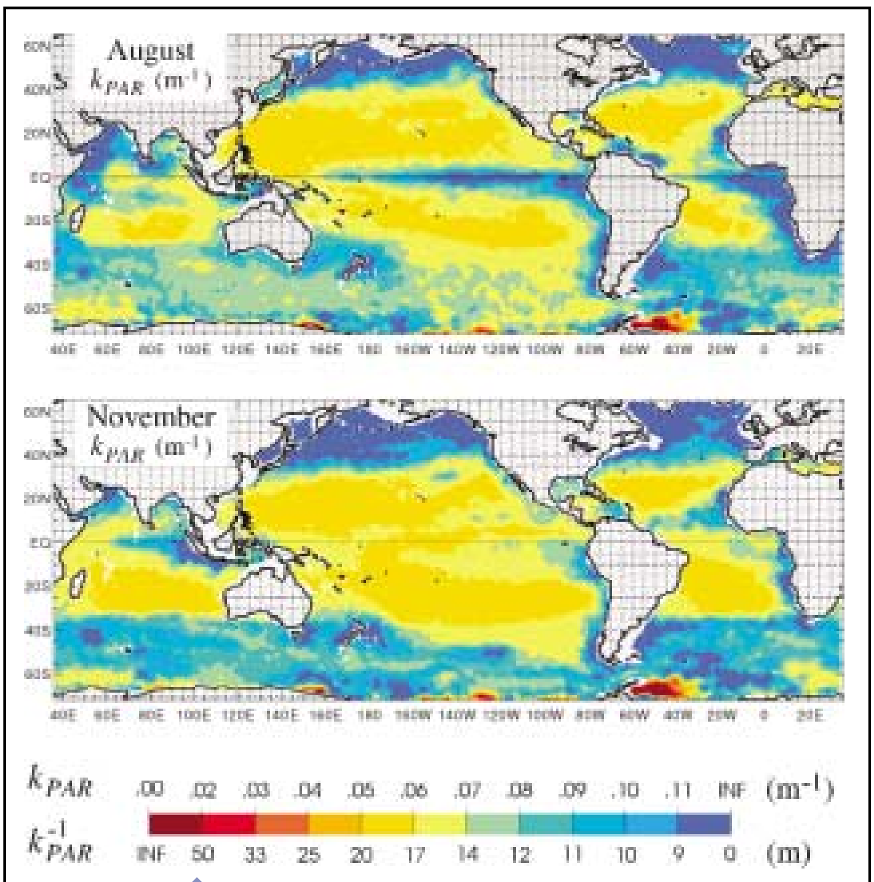

Figure 2. *Global attenuation of PAR [k(PAR)] for the middle month of the northern hemisphere summer (August) and autumn (November).*

mean SST increased by 0.2 to 0.8 ºC and is predominantly confined to the mid and low latitudes (40 ºS to 40 ºN). These differences reflect changes in seasonal variability of SST that can be as large as 1 to 1.5 ºC. The SST increase in the low and mid-latitudes overlaps with where optical depths [k(490)–1] are 14 to 20 m (Figures 1 and 2).

As shown in Figure 3, water optical properties have the largest positive SST changes (~1 ºC) in the western equatorial Pacific, the equatorial Indian Ocean, and the northern low-latitude eastern Pacific. These regions coincide with the large seasonal variability in k(PAR). While these changes in SST might appear small, they can result in appreciable increases or decreases in heat exchange with the atmosphere. For example, for the central Arabian Sea (61.5 ºE, 15.5 ºN) the difference in heat flux when using the SST obtained with and without subsurface heating can be as large as 20 to 45 Wm-2. These changes in heat exchange could alter weather patterns and impact global warming predictions.

Summary

Seawifs remotely-sensed observations of PAR and k(PAR) provide unique information for thermodynamic ocean models and thereby improve our understanding of how the ocean and atmosphere are coupled. The Seawifs k(PAR) presented here has already been implemented in a fully eddy-resolving, data assimilative global ocean prediction system with 1/16º horizontal resolution (Metzger et al., 2001). The latter has been transitioned to the Naval Oceanographic Office and is currently being evaluated for operational use by the Navy fleet.

SST prediction is one area of ocean modeling that has an immediate impact upon our daily lives, namely what the weather will be like today. However, there are also other areas that could eventually lead to real world benefits. One of these is using PAR and k(PAR) to characterize the subsurface light field for ocean microorganisms (e.g., phytoplankton and zooplankton). There are now many bio-physical coupled ocean models under development that are attempting to predict the distributions of microorganisms using simple ecosystem models. They are the first attempts at predicting the lowest levels of the food chain in the world's fisheries, and in time may develop sufficient predictive skill to be of benefit for seasonal predictions of commercial fishing harvests. It is our hope that the data sets we have constructed will be one of the many research resources used towards achieving this goal. Our k(490) and k(PAR) data sets can be made available to any Seawifs authorized user. ■

Acknowledgements

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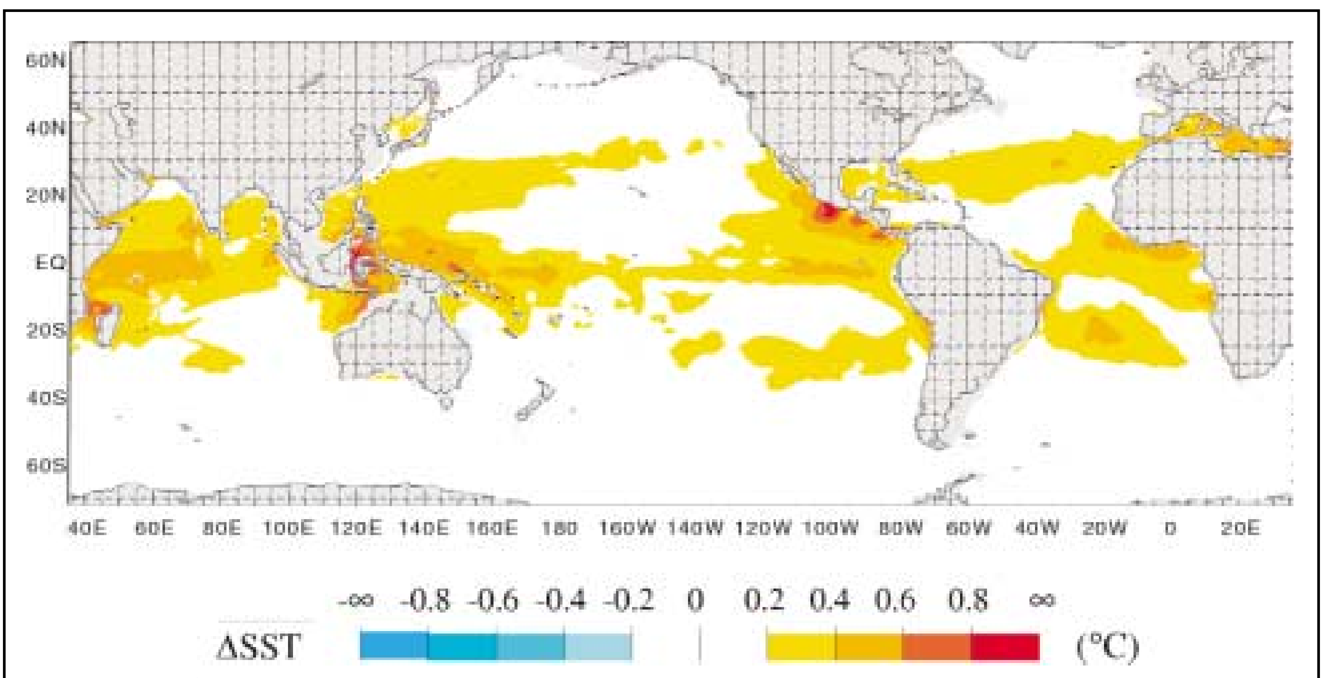

Figure 3. *Annual mean difference in OGCM SST (DSST) when neglecting and using attenuation of PAR. Shown is the SST when all the PAR is absorbed within the mixed layer minus the SST when the PAR is attenuated using a monthly varying k(PAR).*

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