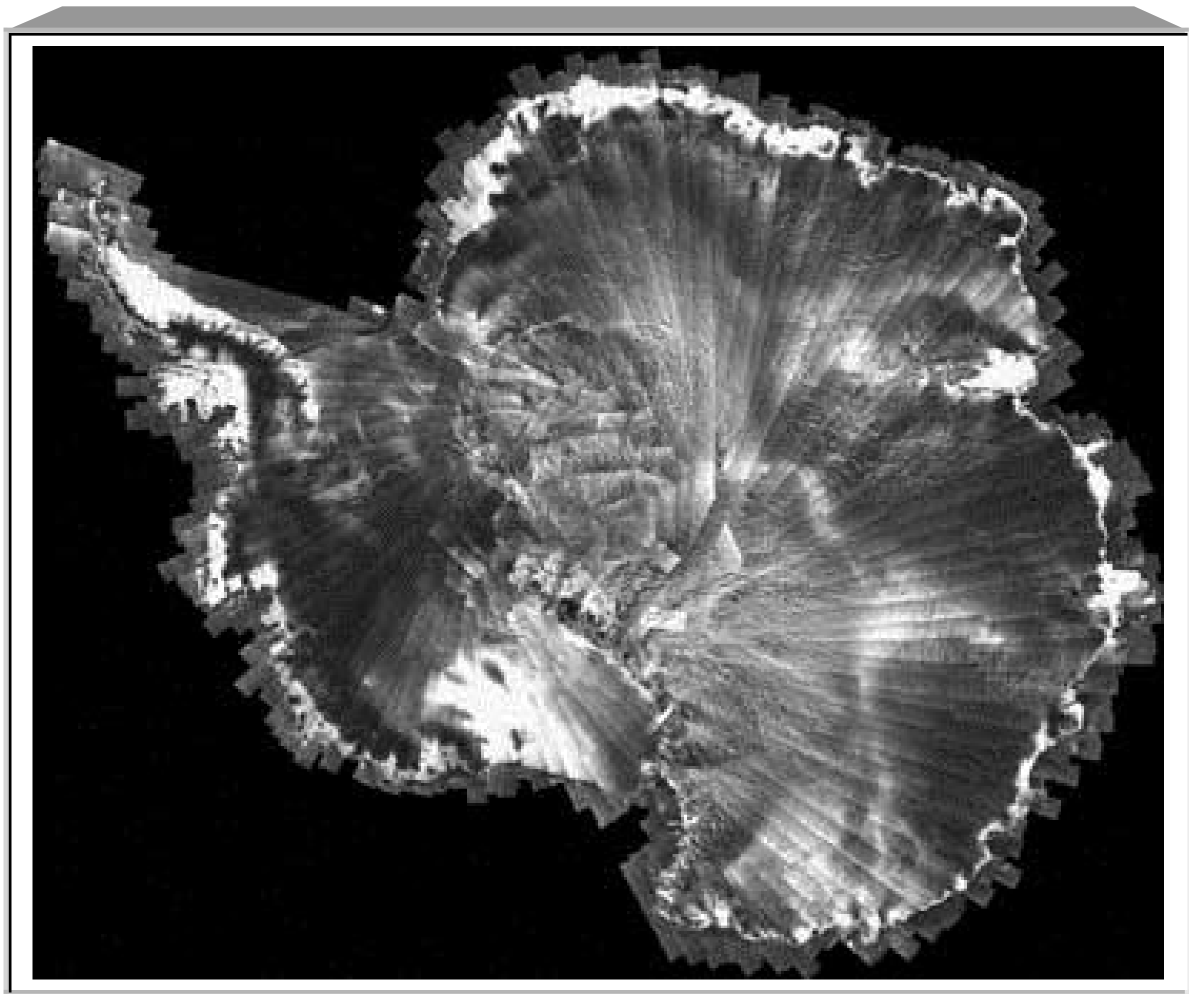
The Critical Role of SAR in Earth System Science



A White Paper by the Alaska SAR Facility User Working Group
Prepared June 1998 for NASA

Cover Note

During the fall of 1997, RADARSAT-1 acquired the first complete high-resolution SAR imagery of Antarctica. As part of this joint Canadian and U.S. project, over 3000 images were quick-look processed by the Alaska SAR Facility and compiled by the Byrd Polar Research Center into the remarkable mosaic shown on the cover. It is indeed a new view of the ice-covered continent, which will enable quantitative analysis of the glaciology, geology and coastal processes of both East and West Antarctica. Over the coming year, an improved mosaic will be constructed using substantially better radiometric and geometric control. The final mosaic will be made available to the international science community for research and educational purposes.

(Figure provided by Kenneth C. Jezek, Byrd Polar Research Center; Copyright CSA 1997).

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Executive Summary and Recommendation

The broad purpose of this document is to encourage NASA to continue and expand its support for scientific and operational exploitation of synthetic aperture radar (SAR) data, both for domestic and global purposes, by demonstrating the critical role of SAR in earth system science. The international agencies that control the constellation of radar satellites have been steadily moving away from the open data policies of the early 1990s toward more restrictive and commercial policies. NASA must take the initiative to negotiate agreements with the foreign flight agencies that will ensure access to data from future spaceborne SAR sensors for the U.S. scientific and operational communities. It is inevitable that the user community will broaden, as onboard tape recorders on the new satellites enable data from all over the world to be downlinked at any receiving station. The cost of purchasing this data directly would be prohibitive; the potential benefits are vast. Thus the specific purpose of this document, the recommendation at the end of this summary, is motivated by the scientific successes and anticipated benefits that are outlined below.

NASA's Mission to Planet Earth Science Research Plan [1996] calls for improved understanding and research in the areas of land-cover and land-use change, seasonal to interannual climate variability and prediction, natural hazards, and long-term climate variability and change. Satellite data are essential to carry out this program and to conduct other earth science research. In particular, spaceborne SAR data have a critical role to play. The NASA report "Spaceborne Synthetic Aperture Radar: Current Status and Future Directions" [1995] states:

> SAR data provide unique information about the health of the planet and its biodiversity, as well as critical data for natural hazards and resource assessments. Interferometric measurement capabilities uniquely provided by SAR are required to generate global topographic maps, to monitor surface topographic change, and to monitor glacier ice velocity and ocean features. Multiparameter SAR data are crucial for accurate land cover classification, measuring above-ground woody plant biomass, delineation of wetland inundation, measurement of snow and soil moisture, characterization of oil slicks, and monitoring of sea ice thickness.

This assessment is confirmed by another remarkable document published in the same month: "Scientific Achievements of ERS-1" [1995], with over 150 pages highlighting the results of the first three years of operation of this European satellite. ERS-1 carried the first satellite-borne SAR widely available to Western scientists since Seasat's brief tenure in 1978. ERS-1 was followed in quick succession by JERS-1, ERS-2, and RADARSAT-1. NASA's Shuttle Imaging Radar (SIR) also made two flights during this time period (see the Table of Spaceborne Synthetic Aperture Radars). To understand this enthusiasm for SAR, consider the characteristics of the sensor and the data:

· All weather day/night imaging capability. SAR penetrates clouds, smoke, haze, and darkness to acquire high quality images of the Earth's surface. This often makes SAR the sensor of choice for the polar regions and tropics alike, assuring timely coverage of target regions, complementing other data sources, and standing in for passive sensors when conditions prevent them from viewing the surface.

· Interferometric potential. This unique capability of SAR can be used for such diverse applications as topographic mapping, surface change detection, and ice stream velocity measurements. The centimeter precision is unmatched by any other remote sensing technique.

· High resolution and multiple beam configurations. Spatial detail on the order of 5 to 30 meters enables complex features to be identified, studied, and tracked in a series of images. Different beam modes on the new SARs allow the angle of incidence, swath width, and polarization to be adjusted for optimal viewing, opening new opportunities for scientific investigation.

· Radiometrically calibrated. This enables quantitative reflectivity analysis, and inter-comparison of data from different locations, seasons, and sensors.

In addition, frequent temporal coverage of most of the Earth is achieved by multiple satellites, polar orbits with short repeat cycles, and the ScanSAR (wide swath) mode of RADARSAT-1. This helps to build long, regularly spaced time series of observations over selected regions, which is necessary for many applications. Some of these applications and recent achievements are presented in the following chapters. Highlights include:

· Land Cover Mapping. Using JERS-1 SAR data, the Global Rain Forest Mapping (GRFM) project is producing a global mosaic of the world's tropical rain forests. This comprehensive, high resolution, dual season snapshot will constitute an unprecedented baseline measurement of the state of one of the Earth's most endangered forest ecosystems.

· Ecology and Agriculture. SAR data have been used to measure increased growing season length in boreal regions as an indicator of global warming; to monitor the extent and frequency of wildfires in boreal regions to better understand the role of biomass burning in the global carbon cycle; to monitor wetlands, which play a key role in greenhouse gas emissions; and to estimate the biomass of several crops.

· Natural Hazards. SAR interferometry can be used to understand local tectonics and seismic hazard vulnerability; to detect surface deformation of volcanoes; and to provide high resolution topographic data for assessing slope vulnerability and detecting ground subsidence. SAR can also provide near real-time monitoring of natural disasters for mitigation and abatement.

· Hydrology. SAR imagery has been used to measure the discharge in braided rivers, and the extent of flooding in large seasonally or catastrophically flooded river systems. SAR interferometry can be used to determine topography, one of the most important factors in watershed modeling. SAR remains essential for the remote sensing of soil moisture and snow melting.

· Oceans and Atmosphere. SAR imagery has been used to identify coastal eddies, surface gravity waves, oceanic internal waves, surface currents, atmospheric lee waves and gravity waves, boundary layer rolls, convective cells and tropical rain cells, and polar lows. Reliable wind vectors may be estimated from calibrated SAR images using the radar cross section, the geometry, and a scatterometer wind retrieval model. SAR is the only sensor that can provide measurements of the directional wave spectrum from space.

· Ice Sheets and Glaciers. RADARSAT-1 SAR recently mapped the entire Antarctic continent at a resolution 30 times finer than previously available. SAR imagery has led to the discovery of large new ice streams in both Antarctica and Greenland. ERS SAR interferometry has detected rapid changes in discharge speed and grounding line position of major outlet glaciers controlling the flow of ice into the world's oceans. The mapping of glacier flow fields to a precision of centimeters per day is far beyond the reach of any other sensor.

· Sea Ice. The RADARSAT Geophysical Processor System (RGPS) is starting to ingest complete weekly SAR coverage of the Arctic Ocean and produce basin-wide fields of sea ice motion, thickness distribution of thin ice, open water fraction, and dates of melt onset and freeze-up. This automated processing of large volumes of SAR imagery into higher-level geophysical products will help modelers and other investigators reap the benefits of SAR data without having to do their own image processing.

· Operational Applications. NOAA and the National Ice Center (NIC) use SAR imagery on an operational basis for sea and lake ice monitoring, iceberg detection, river ice jam monitoring, fishing enforcement, oil spill detection, wind and storm information, and flood mapping.

The U.S. has launched and operated SARs of its own in the past. Seasat, despite its short lifetime, demonstrated the value of SAR for oceanographic and polar research [Fu and Holt, 1982], while the SIR missions aboard the Space Shuttle did the same for land applications. The U.S. is planning to put LightSAR in orbit in 2002, but there is currently no U.S. SAR. We rely on foreign satellites (European, Canadian, and Japanese) to collect the data for us.

However, we do have a receiving station: the Alaska SAR Facility (ASF) in Fairbanks. ASF is unique among NASA's Distributed Active Archive Centers (DAAC) in receiving direct downlink data as well as processing, archiving, and distributing it. In addition, SAR data acquired at McMurdo (Antarctica) and foreign ground stations are sent to ASF for processing. ASF has played an essential role since 1991 in getting SAR data from ERS-1, ERS-2, JERS-1, and RADARSAT-1 into the hands of U.S. researchers and operational agencies.

Several new satellites carrying SARs are scheduled for launch in the next five years: the European ENVISAT-1 (2000), the Canadian RADARSAT-2 (2001), the U.S. LightSAR (2002), and the Japanese ALOS (2003). While the European, Canadian, and Japanese missions may be thought of as continuations of the current generation of SARs, they all add important new capabilities: ENVISAT-1 Advanced SAR (ASAR) has a ScanSAR mode and dual polarization; RADARSAT-2 has a ScanSAR mode like its predecessor and full quadrature polarization; LightSAR is fully polarimetric and is designed with interferometric applications in mind; ALOS has a ScanSAR mode, dual polarization, and is particularly well designed for land cover mapping. U.S. scientists and operational agencies need access to the data from this next generation of advanced SARs for several reasons:

· Data continuity. The prospect of a SAR data record extending well into the next century gives impetus to current research and opens the door to change detection studies on decadal time scales. For example, a mosaic of Antarctica with ENVISAT-1 ASAR (proposed) would enhance the value of the current mosaic made from RADARSAT-1 imagery.

· Multi-polarization. This capability of the new SARs offers the potential for better discrimination of surface types such as ice / water (in sea ice images) and soil moisture (in land images).

· Complementary to EOS / AM-1 sensors. The information provided by these SARs can be used to augment data from sensors such as MODIS, an imaging radiometer with a resolution of 250 to 1000 meters.

· Past and present investment of resources. These upcoming instruments provide the assurance that since SAR data will be available for the foreseeable future, it is worth the continuing expenditure of resources to develop, improve, and implement algorithms and systems to utilize these data.

NASA has done a commendable job in cooperating with the Europeans, Canadians, and Japanese on data reception and access for ERS-1, JERS-1, ERS-2, and RADARSAT-1. Now is the time to continue that cooperation by negotiating new agreements with the European, Canadian, and Japanese flight agencies for ENVISAT-1, RADARSAT-2, and ALOS SAR data. We, the ASF User Working Group, are charged by NASA to make recommendations to promote the advancement of science based on synthetic aperture radar data. Therefore we make the following recommendation with the strongest possible emphasis:

> We recommend that NASA enter into agreements with the European Space Agency (ESA), the Canadian Space Agency (CSA), and the National Space Development Agency (NASDA) of Japan, for the reception of ENVISAT-1, RADARSAT-2, and ALOS SAR data at the Alaska SAR Facility and the McMurdo receiving station; and for access to the global SAR data acquired by these instruments, through the shipment of such data from foreign ground stations to the Alaska SAR Facility or directly to U.S. investigators. These agreements must be negotiated as soon as possible to ensure an uninterrupted flow of SAR data to the U.S. scientific and operational communities.

We believe that the following chapters justify this recommendation and prove our point about the critical role of SAR in earth system science.

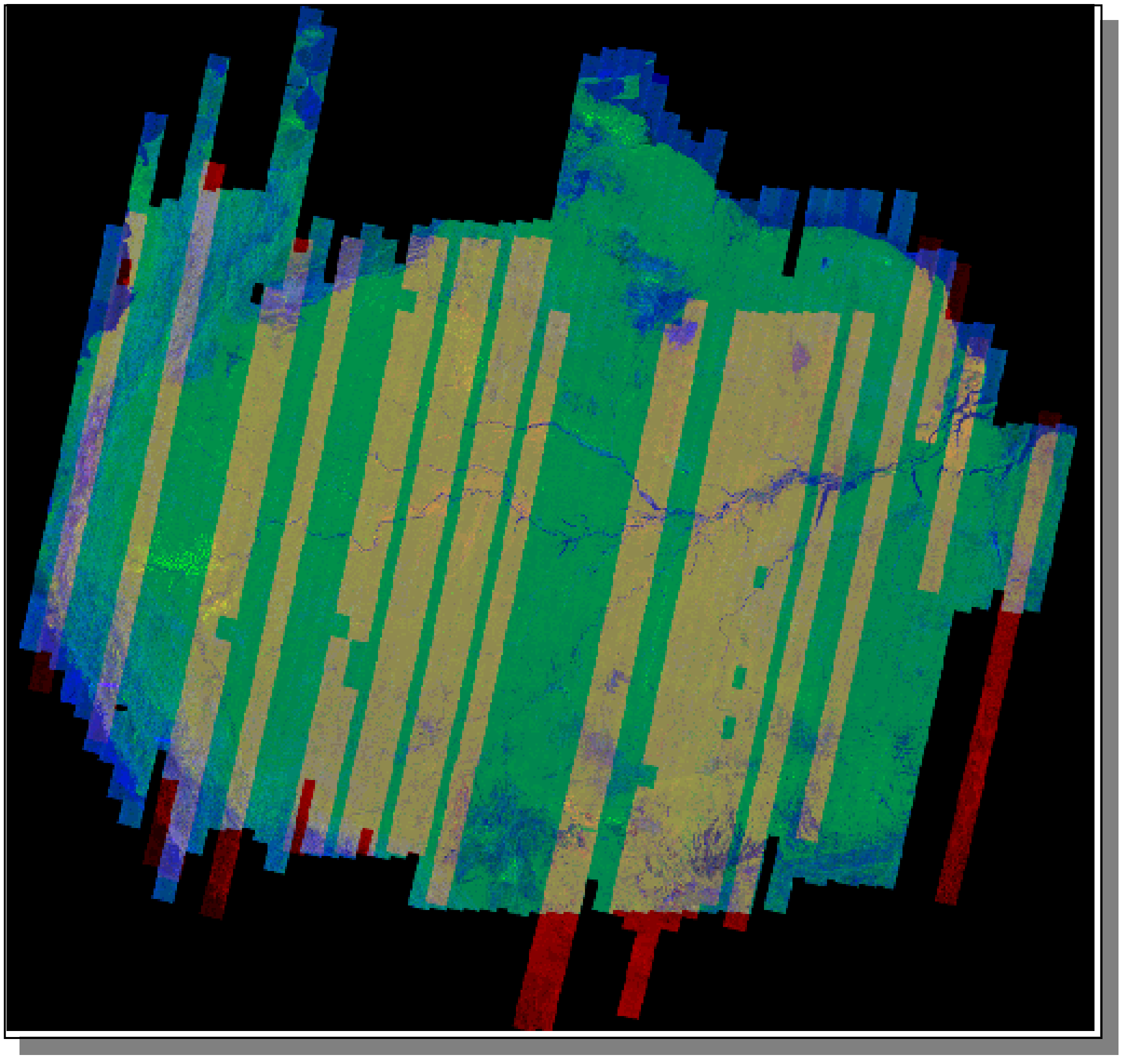
1. Land Cover Mapping

Land cover and land use change research are major science priorities for NASA's Earth Science Enterprise. Few landscapes on Earth have not or are not being altered by humans. Changes in land cover and land use are pervasive, increasingly rapid, and have a suite of interactions with the climate system and human societies. Increasing pressure for food and land will lead to changes in land cover and land use that cannot be currently predicted. As a result, a major research priority is to develop a capability to perform repeated global inventories of land cover and land use from space, and to develop the scientific understanding and models necessary to evaluate the consequences of observed changes.

While land cover is an important element of global and regional modeling of the atmosphere and biosphere, traditional land cover maps tend to have insufficient detail, inconsistent accuracy, variable nomenclature, and are created from data sources that are often outdated. SAR instruments can be major contributors to improving our current capabilities to inventory changes in land cover and land use and thereby provide relevant information to specialists in charge of understanding these changes and predicting their future evolution. A main, obvious advantage of SAR is its all-weather, day and night capability to provide image data from anywhere on the planet. This capability is especially critical in tropical regions where cloud cover severely limits the acquisition of satellite optical data and the possibility of frequent assessment of changes in land cover and land use. In addition, SAR provides important characteristics of soil and vegetation covers that are not well revealed by passive sensors such as Landsat and SPOT: for instance, inundation below closed canopies, fresh woody biomass of forested areas, freeze/thaw conditions of soil and vegetation, soil moisture and surface roughness in areas of low vegetation, and information on the orientation and structure of objects on the ground that reflect the incoming microwave radiation. These and other capabilities promise enormous potential for data fusion between SAR and optical sensors to improve upon our current capability of performing global remote sensing of changes in land cover and land use.

A number of international global change initiatives have identified the need for improved land cover data sets. Data from the ESA ERS and NASDA JERS SARs have been and are currently in use by international research groups to provide comprehensive mapping of tropical rainforests in South America (Figure 1.1), Africa, and Southeast Asia; and boreal forests from the entire circumpolar belt. The Committee on Earth Observing Systems (CEOS) has initiated the Global Observations of Forest Cover (GOFC) program to address the international cooperation required to coordinate land cover mapping activities around the world. NASDA, a participant in GOFC, is leading the Global Rain Forest Mapping (GRFM) project, and the Global Boreal Forest Mapping (GBFM) project, and plans to continue these land cover mapping activities with NASDA's Advanced Land Observing Satellite (ALOS) in cooperation with their international partners (NASA and the European Commission's Joint Research Center). The GRFM project is working closely with the Brazilian/NASA Large-scale Biosphere-Atmosphere (LBA) experiment to provide a remote sensing framework for the *in situ* field work being conducted in Brazil (Figure 1.2). ASF contributes significantly to these projects through its data acquisition and data processing activities. Through the GRFM project, ASF-processed imagery will result next year in a global mosaic of the world's tropical rainforests. This comprehensive, high resolution, dual season snapshot will constitute an unprecedented baseline measurement of the state of one of the Earth's most endangered forest ecosystems.

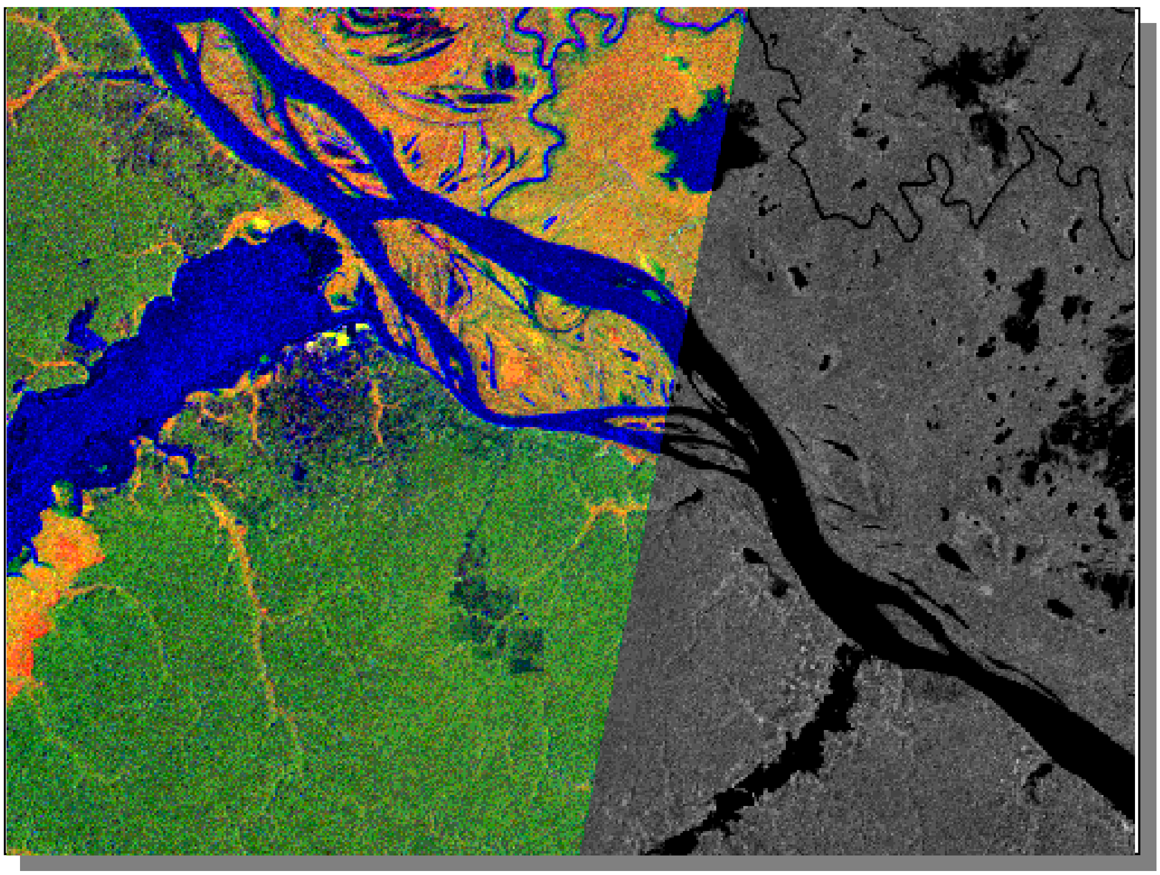
FIGURE 1.1



A mosaic of the imagery of the Amazon basin obtained by the JERS-1 SAR. Data obtained in October 1995 are shown in green. Data obtained in May 1996 are shown in red and blue.

SAR data to be collected by ENVISAT-1, RADARSAT-2, and ALOS are critical to the continuation of these efforts well into the next century. Each of these satellites will carry an on-board recorder, making global coverage more readily accessible. In addition to providing a longer time series of observations that will be highly complementary to that provided by the EOS suite of instruments, these new SAR sensors will significantly enhance our current capabilities to map land cover and land use because they will operate with multiple polarizations and large swath widths. Results obtained in the past with multi-polarization systems such as the NASA/JPL AIRSAR and NASA SIR-C instruments fully illustrated the added value of multiple polarization systems for land cover mapping applications. ALOS SAR has been optimized by NASDA for land cover mapping applications and should therefore receive top priority. ENVISAT-1 and RADARSAT-2 capabilities will, however, provide a significant complement of information, continuation of the initial mapping efforts from ERS-1/2 and ENVISAT-1, and additional SAR coverage. SAR can also provide the topographic information necessary to operate land cover mapping with confidence over rugged terrain. While NASA's SRTM project will provide global topographic coverage between 60 N and 60 S, the international SARs (ALOS, ENVISAT-1, and RADARSAT-2) will provide additional critical coverage in other regions (e.g., the boreal biome). Access to these SAR data by the wide scientific community is critical to the pursuit and sustainability of NASA-funded research enterprises in land cover mapping.

FIGURE 1.2



JERS-1 imagery of Tefe, Brazil, on the Rio Solimoes, in black & white (low flood), and multi-season in color (low and high flood). The color image was formed by assigning the red and green colors to the high and low flood SAR backscatter values, respectively, and the blue color to the texture of the high flood backscatter values. Areas of flooding are yellow, rivers are black or blue, and low vegetation is dark green. The pixel size is 100 meters.

2. Ecology: Natural and Agricultural Ecosystems

Knowledge of terrestrial ecosystems is critical to our understanding of the various facets of global change. Changes in the structure and function of terrestrial ecosystems reflect human and natural influences and in turn influence the quality and sustainability of life on Earth. Global studies and global climate models, in particular, are limited by uncertainties and lack of data concerning the spatial and temporal distribution of terrestrial phenomena including vegetative biomass and productivity in natural and agricultural systems, sources and sinks of important greenhouse gases, biogeochemical dynamics, and land use/land cover change due to natural or human impacts. Over the past decade, satellite-borne SAR has proven to be an important and essential sensor to address these and other terrestrial processes.

The information garnered by imaging radars is fundamentally different and thus complementary to that detected by visible and infrared systems and, although extremely valuable, optical satellite data is often limited in many terrestrial applications by cloud cover, low illumination conditions, low spatial resolution, infrequent acquisitions which preclude seasonal studies, and an inability to penetrate the vegetative cover to characterize the surface. SAR, on the other hand, provides its own illumination at frequencies that can penetrate clouds and smoke to provide information at high spatial and temporal resolution within and below the canopy.

Waring et al. (1996) and Kasischke et al. (1997) summarize many of the advantages and successes in the use of SAR to address a variety of terrestrial processes. Way et al. (1997) used ERS-1/2 to measure increased growing season length in boreal regions as an indicator of global warming. ERS-1/2, JERS-1, and RADARSAT-1 SAR have proven useful in monitoring the extent and frequency of wildfires in boreal regions to better understand the role of biomass burning in the global carbon cycle [Kasischke et al., 1997]. Morrissey et al. (1996) also demonstrate how significant improvements in estimates of global carbon exchange would result from multitemporal analyses of inundation and thus the partitioning of the landscape into seasonally aerobic and anaerobic areas. Similar studies addressing the extent and timing of flooding in tropical studies using ERS-1/2 and JERS-1 SAR have also met with success. The success of these seasonal studies is due, to a large degree, to the unique and reliable multitemporal capabilities of SAR.

Wetlands play a key role in greenhouse gas emissions, as breeding sites for vector-spreading disease, and as highly productive ecosystems in terms of biomass and species diversity. SAR sensors are particularly well suited to monitoring wetlands because of their special ability to penetrate vegetation canopies and thus to detect underlying flooding [Waring et al., 1996]. Observational data from ERS-1/2 and RADARSAT-1 have proven successful in monitoring river flooding, tidal changes in coastal estuaries, and standing water in boreal wetlands [Kasischke et al., 1997]. The alarming increase in vector-borne diseases associated with wetlands has become a major world health issue. SAR has successfully mapped malaria breeding habitats in Kenya, Mexico, and Belize [Pope et al., 1997].

The utility of radar to map aboveground biomass has been documented in temperate and tropical coniferous and deciduous forests [Ferrazzoli et al., 1997; Kasischke et al., 1997; Waring et al., 1996]. In agricultural areas it is particularly important to measure crop growth and vigor on a frequent basis. Since many of the important agricultural regions of the world occur in humid environments, frequent temporal coverage by optical sensors is difficult because of cloud cover. In addition, optical satellites typically cannot assess changes in broad-leaved vegetation amount beyond a leaf area index of about three because of saturation effects. In contrast, very promising results have been obtained for estimating biomass of several crops using C-band SAR data [Le Toan et al., 1997; Ferrazzoli et al., 1997].

It is essential to monitor the world's forests to understand ecosystem dynamics, global climate change, and the impacts of human activities. Using JERS-1 SAR data, the Global Boreal Forest Mapping (GBFM) and Global Rain Forest Mapping (GRFM) projects will provide, for the first time, satellite mosaics in support of global forest research (see Figure 1.1). Information on species composition, stem density, structure (e.g., for forests: trunk diameter, tree height, crown size), leaf area index, basal area, and total biomass derived from SAR has been incorporated within models to study forest growth, competition and mortality [Kasischke et al., 1997; Waring et al., 1996].

The availability of ENVISAT-1 ASAR, RADARSAT-2, ALOS, and LightSAR data during this next decade is critical for continued monitoring of these key processes. The combination of multiple channels and polarizations of this next generation of SARs offers even greater promise for estimating total biomass because of SAR's unique capabilities to distinguish woody from herbaceous biomass and to penetrate the vegetative canopy to detect underlying surface conditions. Cross-polarization SARs have been shown to be superior for estimating aboveground biomass. The radar backscattering for SARs operating at shorter wavelengths such as C-band (~6 cm) primarily occurs in the upper part of tree canopies and throughout most agricultural crops. This frequency, therefore, is sensitive to leaf and branch shapes and orientations, and thus these systems are important for discriminating between vegetation types. Cross-polarization signatures have also shown more sensitivity to the crown structure than the like-polarization signature. ENVISAT-1 ASAR, RADARSAT-2, ALOS, and LightSAR with their combined multiple frequency and multipolarization capabilities, should provide the best data of vegetation type and amount since the SIR-C/X-SAR missions in 1994.

Continuity of SAR data acquisition with RADARSAT-2 and ENVISAT-1 ASAR provides the basis for assessing natural and anthropogenic changes on the surface of the Earth which can be used to determine states and rates of ecological processes. Losses of carbon due to biomass burning or wetland conversion to agricultural use, enhanced positive feedbacks to climatic warming, resource management, and agricultural productivity are and will continue to benefit from the use of multitemporal SAR, particularly in those northern and tropical regions of the world where extensive cloud cover precludes the acquisition of optical data. Further, long term studies requiring time series analyses based on satellite data in these cloud-covered regions are, to a large degree, limited solely to active microwave data such as SAR. Without SAR data, scientific research in these regions would lack the critical information needed regarding the spatial and temporal distribution of ecological phenomena important to global change.

3. Natural Hazards

Thousands of human lives and billions of dollars are lost every year to natural disasters. However, recent developments in the use of orbital radars demonstrate that NASA scientists can assist society in reducing these losses, and help mitigate the losses of life, casualties, and economic disruptions from future natural disasters. Based on previous experiences under the SIR-C/X-SAR and ADRO programs, U.S. radar scientists can be effective in developing a greater understanding of natural hazards, characterizing natural disasters, and monitoring conditions that may lead to such events. Because natural disasters cross political borders and may have far-ranging international consequences, the all-weather, day/night orbital perspective provided by radars such as ERS-2, RADARSAT-1, and JERS-1 is a powerful component of NASA's natural hazard research effort.

The analysis of natural hazards is one of the five principal objectives of NASA's Office of Earth Science. To this end, there are several missions and mission concepts being considered for future U.S. radar systems that will support natural hazards research. It is crucial that the U.S. research community continues to participate in algorithm development, applications research related to natural hazards, and the analysis of existing data sets from foreign partner radars so that temporal effects can be considered. Based on NASA's goals for natural disaster investigations, the U.S. radar community could take a leading role in the analysis of the following solid earth investigations:

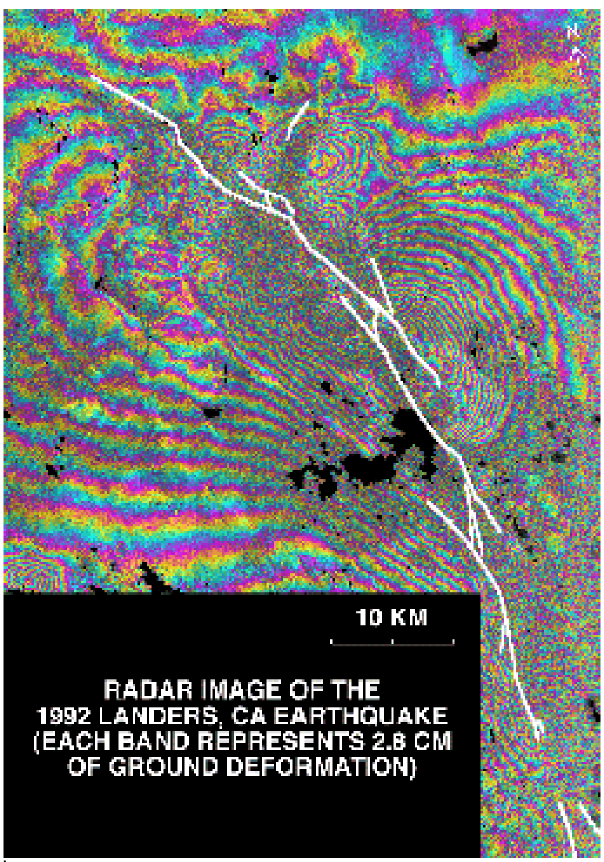
1) Seismic Hazards: Synthetic aperture radar interferometry (InSAR), in conjunction with advanced space geodetic techniques such as the dense Global Positioning System (GPS) array, can be used to improve our ability to understand local tectonics [Massonnet et al., 1993] and to relate these to seismic hazard vulnerability. Radar interferometry can best be conducted with ERS-2 data due to the stability of the spacecraft orbit, but some successes have also been achieved with JERS-1 and RADARSAT-1 data. Key to this research is the development of data sets that cover extended periods of time so that co-seismic and inter-seismic effects can be studied (Figure 3.1). Limitations of the interferometry technique, such as atmospheric effects and the selection of optimum spacecraft baselines, also require many sets of observations [Zebker et al., 1997].

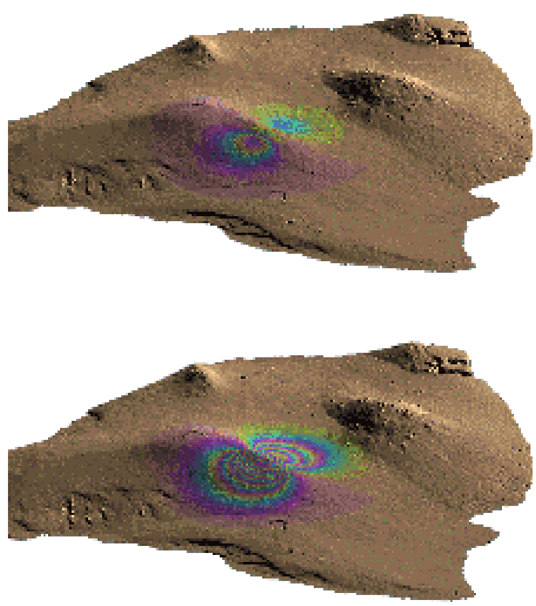
2) Short Term Climate Variability: NASA is poised to improve the quality of local and regional flood forecasts and risk assessments using watershed models incorporating satellite-derived parameters such as topography, land cover, recent rainfall history, soil moisture, snow cover (or its water equivalent) and snow melt. Similarly, forecasting of other extreme events may be regionally sharpened by satellite land cover time series and snow accumulation and snow melt forecasting in regional drainages. In both cases, regional mapping using radar data sets will enable the land surface to be better characterized. Radar data from any of the currently flying systems can contribute to this study, but additional progress is expected when radar systems with a spatial resolution of less than 5 meters/pixel (e.g., RADARSAT-2, LightSAR) become available.

3) Wildfires: The emphasis in the near future will be on characterization (location and intensity) and modeling of wildfire development based on the understanding of local vegetation conditions and topography. The development of short term vulnerability assessments would be greatly aided by the production of digital topographic maps via InSAR (either repeat-pass ERS-2 data, or SRTM), and the estimation of soil moisture and canopy structure via multi-polarization radar data (e.g., ENVISAT-1 ASAR).

4) Volcanic Hazards: New capabilities to monitor precursor activity and ongoing activity at a volcano using orbital radar capabilities have been developed over the last five years. Most important have been the ability to conduct topographic mapping, detect surface deformation [Massonnet et al., 1995; Rosen et al., 1996], and map areas of surface change (e.g., the size of new lava flows) through InSAR [Zebker et al., 1996] (Figure 3.2). Digital elevation models can also be used to predict the most likely paths of lava flows, lahars, and pyroclastic flows, thereby enabling advance training on hazard mitigation to be directed towards populations at greatest risk. ERS-2 is the most suitable orbital radar currently flying for this application due to the stability of its orbit. However, the 35-day repeat cycle is too long to observe highly dynamic events, so that a radar with variable viewing geometry (e.g., ENVISAT-1 ASAR, RADARSAT-2) or a short repeat cycle (LightSAR) would be more suitable.

FIGURE 3.1



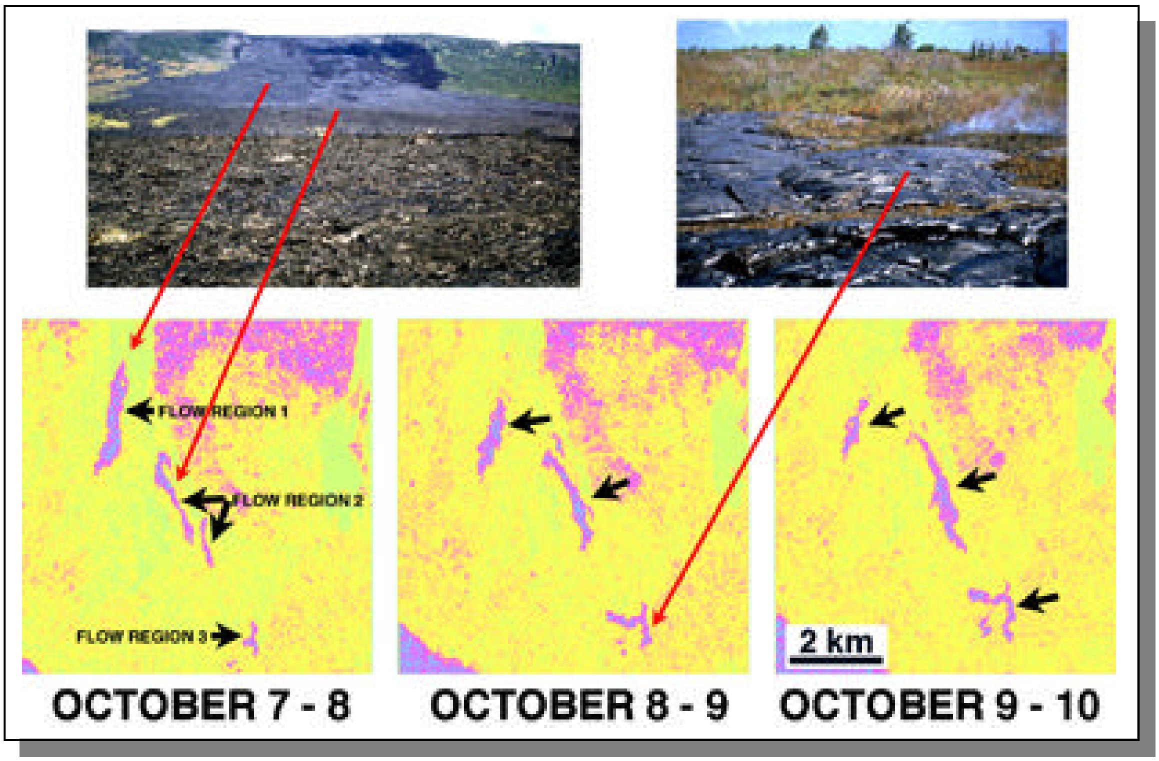


TOP: Simulation of a radar interferogram of the island of Hawaii depicting deformation from magma flowing through a crack in the rock from 6 miles deep (top) to within 1/2 mile of the surface (bottom). Soon after the second image lava would break out of the surface and threaten property and lives alike.

LEFT: Radar interferogram from ERS-1 SAR showing surface displacements from the 1992 Landers, CA earthquake. The faults involved are shown in white. Each "fringe" represents 2.8 centimeters of surface deformation. (Image courtesy G. Peltzer / JPL).

5) Landslides and Ground Subsidence: Radar interferometry can provide a high-resolution topographic data set for assessing slope vulnerability. Surface change detection due to ground subsidence (Figure 3.3), and the downslope movement of material by slow creep, could also be detected [Massonnet and Feigl, 1995]. Choice of radar sensor will depend critically on the range of slopes being investigated; landslides preferentially form on steep slopes that would be imaged with extreme lay-over by ERS-2, or might be in radar shadows in RADARSAT-1 Beam 6 and 7 images. Vertical movement due to subsidence would best be detected by ERS-2 or Beam 1 of ENVISAT-1 ASAR data.

FIGURE 3.2



Interferometric SIR-C data were used to study the growth of a lava flow field in Hawaii over a four day period (October 7-10, 1994). Three regions of active flows (black arrows in bottom diagrams) were identified on successive days using the radar data, from which the surface area of the new flows was estimated. Field observations of these same flows (top images) showed that they had an average thickness of ~50 cm, thereby enabling the volume of erupted material to be estimated at ~2.0 cubic meters per second [Zebker et al., 1996].

6) Coastal Hazards: The near-shore coastal environment offers a unique setting where geologic, ecologic, oceanographic and meteorological factors can lead to extreme storm surges, regional subsidence, flooding, regional bathymetric changes due to sediment redistribution/resuspension, pollution concentration/dispersion. Radar studies can offer significant insights into coastal hazards due to the ability of radar to accurately map the water/land interface (JERS-1 or some RADARSAT-1 modes), near-shore shallow bathymetry (ERS-2), and the area of flooding following a storm surge (JERS-1, or some RADARSAT-1 modes). RADARSAT-2 and ENVISAT-1 ASAR will also be

suitable for these studies with the additional advantage that the steerable antenna will decrease the time between observations (albeit at different viewing geometries).

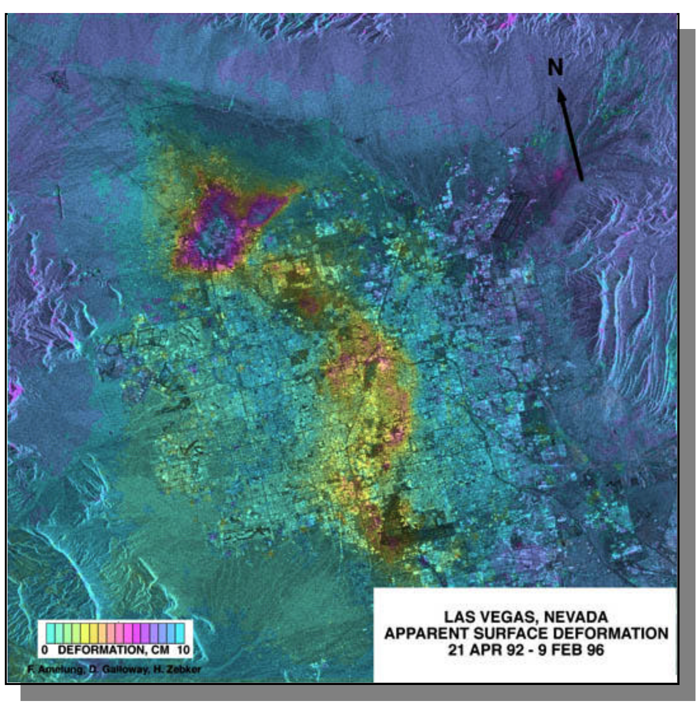
Some of the key areas where there is a strong U.S. radar community participation in natural hazards research are described below:

1) SAR Interferometry (InSAR) enables topography, surface deformation, and change to be investigated. Several science results related to earthquakes, volcanoes, and ground subsidence have already been published using ERS, JERS-1 and SIR-C data sets.

2) The proposed third flight of the SIR-C/X-SAR is dedicated to providing a digital topographic data set over all of Earth's land surface between 60N and 60S. Current plans call for the Shuttle Radar Topography Mission (SRTM) to fly either in 1999 or 2000. These data will have ~13-16 meter vertical and 30 meter horizontal resolution. If acquired, this topographic database will provide important information in assessing the risk of floods and landslides, aiding the analysis of geologic landforms [e.g., Rowland, 1996], and providing an important baseline against which topographic change can be compared in subsequent SAR interferometric observations.

3) The LightSAR project is being considered by NASA as a technology demonstration mission, including the most recent advances in composite materials and hybrid structures (low mass, compact foldable antenna) and microelectronics (low power). Commercial applications for these data are being sought, and one area where a large user base may exist is in the mitigation of risk due to natural hazards. However, the full potential of LightSAR will only be realized when the research community has access to an orbital radar with a highly stable, short-repeat (8-10 days) orbit, thereby enabling frequent interferometric observations to be made. Research community participation in algorithm development for the rapid processing and interpretation of these data, as well as the analysis of the high spatial resolution data that the commercial sector demands, will also facilitate hazards research.

FIGURE 3.3



4. Hydrology

As discussed in the National Research Council's "Opportunities in the Hydrologic Sciences" [National Academy Press, 1991], hydrologic science is metamorphosing from a narrowly focused engineering discipline into one of the fundamental components of earth system science. This change is driven by the recognition of the fundamental role of water throughout earth systems. The growth of hydrologic science is largely enabled by the rapidly evolving observational technologies of satellite remote sensing during the past three decades. Satellite remote sensing can bridge the gap in spatial scale from local point or field scale measurements of traditional hydrology to the regional and global scales critical to modern earth system science. Synthetic aperture radar (SAR) has a particularly important role in hydrologic science because of its ability to see through clouds and darkness, its high spatial resolution, and its unique sensitivity to the presence of liquid water. Interferometric SAR adds the powerful new abilities to determine topography and topographic change with revolutionary applications to watershed modeling, natural hazards, and glacier and ice sheet dynamics.

The basic requirements for hydrological research in the context of earth system science are regionally and globally comprehensive time series of relevant measurements. The capability for developing long continuous time series from high resolution SAR observations began in 1991 with the ERS-1 SAR, has continued with the additions of JERS-1, ERS-2, and RADARSAT-1, and will continue in the future with ENVISAT-1, RADARSAT-2, ALOS, and LightSAR. For the U.S. scientific community, ASF is the primary window of access into these missions with the capability of developing large and scientifically effective multi-temporal sequences of high resolution images. In fact, it can be argued that this will remain the primary window into large, high spatial resolution multi-temporal sequences of any type for some time to come.

It is thus essential that the ASF window into multi-temporal SAR data continue with the acquisition of data from the new SARs that emerge internationally or nationally. The availability of SAR data from several platforms significantly increases the frequency with which observations can be made, thereby greatly enhancing the value of the time series. For many hydrological investigations, particularly those falling under the priority science themes "Seasonal-to-Interannual Climate Variability and Prediction" (e.g., watershed response) and "Natural Hazards Research and Applications" (e.g., flooding), the development of unaliased time series spanning synoptic to inter-annual time scales is essential. The continuity of the series of SAR observations extends from ERS-1, ERS-2 to ENVISAT-1, from RADARSAT-1 to RADARSAT-2, and from JERS-1 to ALOS. This continuity, combined with the fact that the three platforms will be mainly flying at the same time, thereby providing increased frequency of observations, has incredible potential for the hydrological component of earth system science. Besides providing continuity and more frequent observations to a growing time series, the new generation of platforms greatly increases the value of SAR with the addition of multi-polarization capability and variable swath sizes and look angles.

This potential of SAR in hydrology has been explored during analysis of data from short term missions such as Seasat, SIR-A, SIR-B, and especially the two SIR-C/X-SAR missions and many of the TOPSAR flights. These studies have demonstrated the power of SAR observations in several major areas of hydrologic science including snow hydrology, glaciology, river processes, tundra hydrology, and soil moisture and wetland extent. Some of the potential applications of SAR in these areas were not even realized just a few decades ago when the SARs of the 1990's were being planned, and undoubtedly significant new potential applications will emerge in the future as SAR data are increasingly exploited by researchers.

Areas of particular promise for the application of new SAR data from ENVISAT-1 and ALOS are outlined below.

Alpine Snow and Ice. Multi-temporal SAR images of Alpine icefields and glaciers of Patagonia and southeast Alaska/British Columbia have revealed well defined and regionally consistent "radar glacier zones" related to the evolution of melting on the glacier surface [Forster, et al, 1997; Smith et al., 1997] (Figure 4.1). The interpretation of these features relies on joint field/satellite studies of glaciers and snow fields in the Austrian Alps and the U.S. Sierra Nevada with ERS-1 data and during SIR-C/X-SAR and TOPSAR missions [e.g., Shi and Dozier, 1997]. The temporal behavior of radar glacier zones is providing key information on the onset and progression of glacier melting that can be integrated into and interpreted by mesoscale atmospheric models of mountainous regions. The goal is to understand the causes of regional glacier change in terms of meteorological processes operating on synoptic to inter-annual time scales, and from this to understand better the causes of glacier changes over the decadal time scales of global climate change.

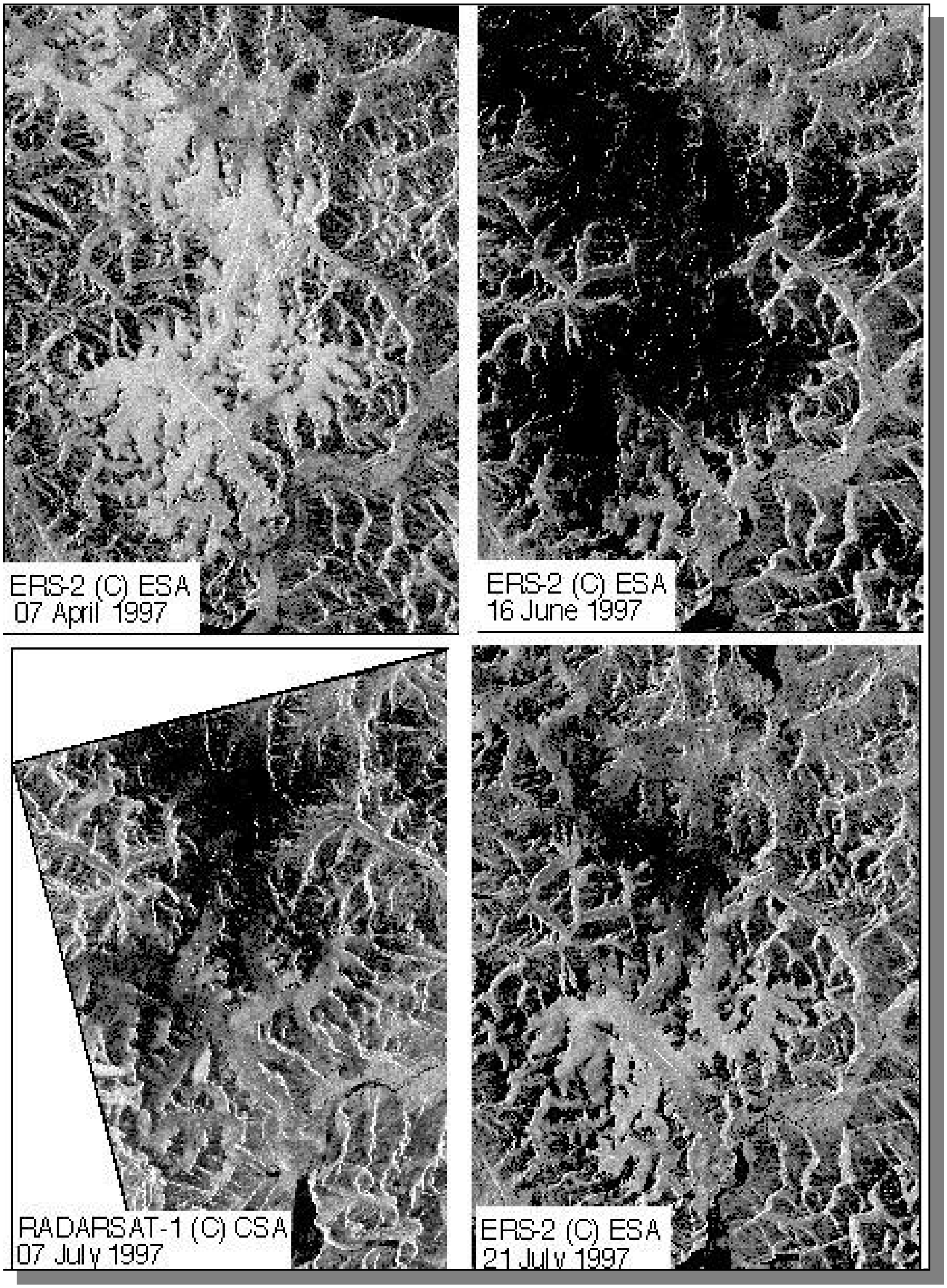
Dense sampling in time and development of multi-year time sequences are essential to this type of study. The ScanSAR modes of RADARSAT and ENVISAT-1 will be especially valuable in providing coverage of large regional spatial scales. The alternating VV-HH mode of ENVISAT-1 will provide important new information on the physical interpretation of the radar glacier zones.

Glacier Extent, Topography, and Velocity. Interferometric SAR has been successfully applied to glaciers in Greenland, Antarctica, Patagonia, and Alaska. With suitable data, vector motions and topography can be obtained. This approach, discussed further in the section on "Ice Sheets and Glaciers", will revolutionize the study of mountain glaciers.

River Discharge, Flooding, and Wetlands. The ability of SAR to detect standing water on terrestrial surfaces has been exploited in several contexts, including the measurement of discharge in braided rivers, the extent of flooding in large seasonally flooded river systems such as the Amazon and the Ob River, and in catastrophic flooding - one of the major natural hazards - such as occurred along the Mississippi and Missouri rivers during the past decade. SAR is also effective in monitoring changes in flood plain scour and deposition produced by major floods [e.g., Izenberg et al., 1997].

Although L-band SARs such as JERS-1 are necessary to map flooding beneath tropical vegetation, the C-band SARs have been shown to be effective in high latitude regions. The seasonal flooding and temporary sequestering of large shallow water masses (see Figure 4.2) is an important component of the biogeochemistry of major river systems.

FIGURE 4.1



Onset and progression to higher elevations of the radar glacier phase characterized by very low backscatter amplitudes and associated with early stages of snow melt. The images are ERS-2 and RADARSAT-1 images of the Juneau Icefield of southeast Alaska [J. Ramage, B.L. Isacks, and M. Miller, in preparation].

A key problem in detecting extended water bodies is the effect of wind-driven waves in increasing backscatter and obscuring the boundaries between water and land. Interferometric SAR coherence over short time periods can bypass this problem in areas where coherence is obtained over the land surface but not over the water surfaces. This technique can be applied to seasonally flooded areas in arctic continental regions of North America and Asia [e.g., Smith and Alsdorf, 1998].

The measurement of water-covered areas in braided rivers by SAR has been shown to provide an estimate of river discharge. Since braided rivers often drain remote, glacierized basins, the SAR measurements can provide important constraints on the meltwater runoff and ablation of the glaciers [e.g., Smith et al., 1996].

Topography. Topography is one of the most important determinants of the hydrological regime - e.g., in watershed modeling and prediction of the extent of river flooding - and its determination at sufficient horizontal and vertical resolution is critical. There will be continued need for topographic data at finer resolution than that which will be available from the planned Shuttle Radar Topography Mission (SRTM), although SRTM will provide a good basis at latitudes below 60 north and south. In order to develop the best image combinations for interferometric SAR – appropriate baselines, combination of ascending and descending looks in regions of high relief, and attainment of coherence – access to as much of the ongoing acquisitions as possible is required.

Soil Moisture. Remote sensing of soil moisture, one of the key elements in both hydrologic science and in the incorporation of land surface processes into GCMs, continues to play an important role in the quest for watershed- to global-scale models. Although the problem remains difficult, two aspects of SAR offer particular promise. First, multi-temporal SAR observations of relative changes in time offer an approach to separate out changes in soil moisture from other effects such as ground roughness and vegetation which may not change on the same time scales as soil moisture. The increased frequency of observations provided by access to all available SARs is also critical for examining the often short time scales over which soil moisture can change. The second important aspect of continued access to ENVISAT-1 ASAR data in particular is the multi-polarization capability, which offers the potential for better discrimination of soil moisture in certain environments [e.g., Dubois et al., 1995; Wang et al., 1997].

FIGURE 4.2

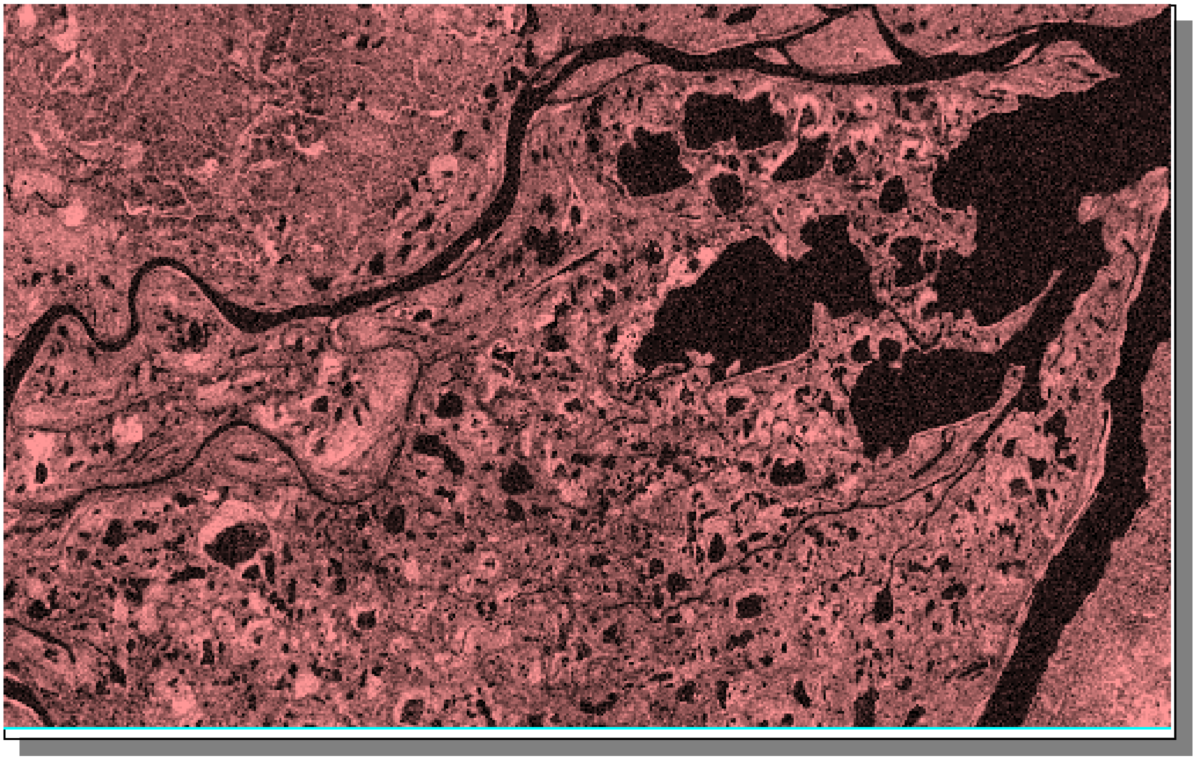


Image of phase coherence between two images obtained one day apart during the 1995 ERS-1/ERS-2 tandem mission. In either of the individual backscatter amplitude images, the delineation of water-covered areas is seriously obscured by wind-enhanced backscatter, whereas the coherence image shown here sharply delineates the water bodies as areas of very low coherence (black). The figure is from Smith and Alsdorf, 1998.

5. Oceans, Coastal Zones, and Atmosphere

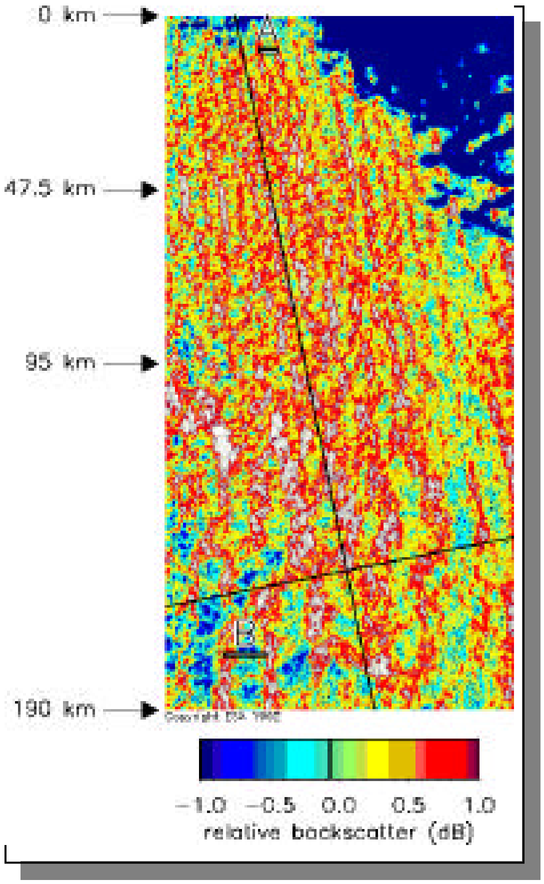
During this decade, satellite sensors such as altimeters and scatterometers have provided extensive time series of upper ocean data. When combined with longer time series from other ocean sensors such as radiometers, the picture of the complexity of upper ocean and coastal zone processes and air-sea-ice interaction has broadened significantly. Large-scale ocean processes are becoming better understood, leading researchers and modellers to probe further into mesoscale (5 km to 500 km scale) processes where significant energy exchanges and air-sea-ice interactions are occurring. Since 1991, the unique and detailed ocean surface information in SAR imagery from ERS-1, ERS-2, and RADARSAT-1 has been used successfully with other ocean sensors, buoy and ship data, and regional wind / wave models to improve our understanding of upper ocean circulation and coastal processes on these scales. With the recent launch of SeaWiFs, continuing scatterometer and radiometer observations, and the prospect with ENVISAT-1 of combining SAR with simultaneous measurements of ocean color and sea surface temperature, we are entering a new era for observations of upper ocean circulation, air-sea interaction, biological productivity, and coastal environmental monitoring.

A SAR image of the ocean's surface provides a map of the roughness distribution at centimeter length scales, at any time of day or night and with little hindrance from clouds. A SAR may image any physical process that modulates the roughness at those scales. The main modulation mechanisms include spatial and temporal variations in wind stress, current shear, and surfactants that damp the short scale waves. In general, many such ocean processes are ambiguously combined in a single SAR image. Under special circumstances or with appropriate supporting data, the ambiguities may be resolved and unique information on the underlying geophysical phenomena may be inferred. Furthermore, SAR is the only sensor that can provide information on the directional ocean wave spectrum from space.

Extensive use of ERS-1, ERS-2, and RADARSAT-1 SAR images of the ocean has allowed a maturing of our understanding of the geophysical content of these images. Progress has been made in the interpretation and utilization of SAR images of surface gravity waves, oceanic internal waves, surface currents, and mesoscale features. Since SAR is the only sensor that can provide measurements of the directional wave spectrum from space, SAR may fill a role in wave forecasting [Breivik et al., 1998; Dunlap et al., 1998] and has provided insight to wave / ice interaction processes [Liu et al., 1994]. The character and evolution of internal waves as they approach the shoreline has recently been documented using ERS SAR images [Liu et al., 1998]. SAR can be used to identify coastal eddies where they cannot be seen by other sensors due to cloud cover, low temperature contrast with surrounding waters, and their size [Nilsson and Tildesley, 1995; Johannessen et al., 1996]. This improves the temporal monitoring of the development and movement of coastal eddies, an important issue in monitoring biological productivity.

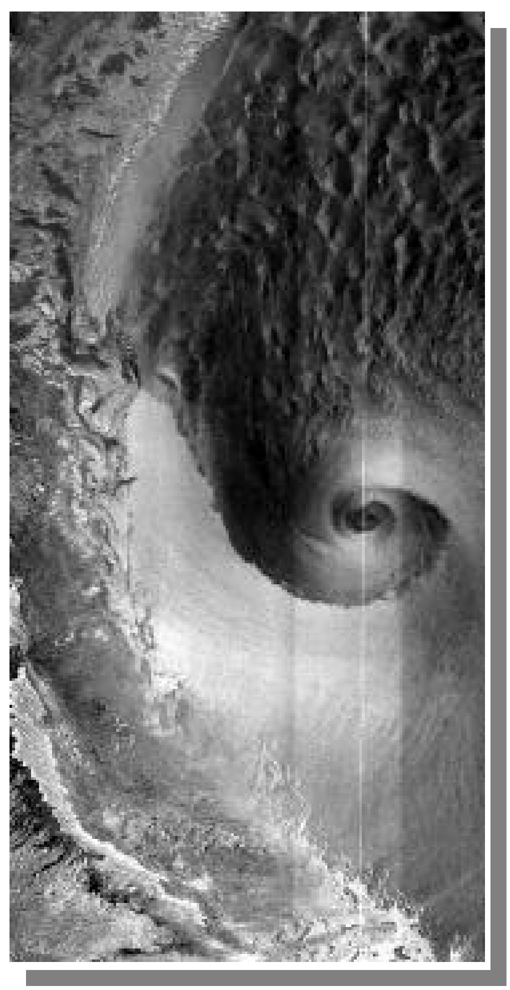
A newer area of research has been the use of SAR images to quantitatively study air-sea interaction phenomena in the atmospheric boundary layer. Case studies of SAR images of atmospheric lee waves and gravity waves [Vachon et al., 1994], boundary layer rolls [Johannessen et al., 1994; Mourad and Walter, 1996] (Figure 5.1), atmospheric surface-layer turbulence [Mourad, 1996], convective cells and tropical rain cells

FIGURE 5.1



The radar backscatter patterns associated with a cold air outbreak in the Bering Sea. Atmospheric flow is from the top of the figure (north) to the bottom, off of sea ice (upper right in blue) and out across the open ocean. The length scale "A" (top) showing the distance between streaks is 5 kilometers, and "B" (bottom) is 13 kilometers. Comparable cloud patterns appear in a nearly simultaneous AVHRR image (not shown).

FIGURE 5.2



RADARSAT-1 ScanSAR wide image of the Labrador Sea acquired on January 30, 1997, at 21:30 UTC, showing a polar low. The area shown is roughly 500 km by 1000 km. (Copyright CSA 1997)

[Jameson et al., 1997], and polar lows [Vachon et al., 1998] (Figure 5.2) have recently been published. Also, the role of SAR as an imaging scatterometer has matured to the point that reliable wind vectors may be estimated from calibrated SAR images using the radar cross section, the geometry, and a scatterometer wind retrieval model [Vachon and Dobson, 1996] (Figure 8.2). A key advantage of a SAR over a scatterometer is the SAR's much higher spatial resolution (100 m vs. 10,000 m), allowing study of smaller, more local scale atmospheric phenomena well into the nearshore regime, opening the possibility of using SAR for ocean surface meteorology and site-specific weather forecasting.

Aside from its use in wave forecasting, SAR data are also being used operationally for ship surveillance (to meet fisheries enforcement as well as defense requirements) and for oil spill and pollution monitoring, including rain run-off from heavily populated coastal areas. Although these applications are considered under operational requirements, other ocean information that can be extracted from the same images, such as the wind vector, can improve user confidence in these applications.

Coastal zones are constantly changing in response to social, economic and environmental forces. These changes can occur over a wide range of spatial and temporal scales. The routine coastal monitoring for many of the processes noted above will be a key application of SAR data fusion. SAR data are highly complementary to SeaWiFS and AVHRR data. SAR responds to different effects from the same phenomena (for example, to changes in wind stress or local current shear rather than directly to the spatial temperature field). Furthermore, SAR is complementary in that it has a different suite of environmental masks (high wind speed for SAR vs. cloud cover for SeaWiFS and AVHRR) and offers high resolution (100 m vs. 1000 m). Using wavelet techniques, schematic diagrams (i.e., line drawings) of these features can be drawn to produce ocean feature maps [Liu et al., 1997]. With more frequent coverage from multiple sensors, such features can be tracked for process studies and compared with results from eddy resolving ocean circulation models.

The opportunity to utilize ENVISAT-1 and RADARSAT-2 SAR data is critical to the ongoing development of SAR applications for the oceans and coastal zones. These upcoming sensors provide data continuity to the current ERS-1, ERS-2, and RADARSAT-1 programs, as well as new operating modes (especially in terms of polarization diversity and spatial resolution) that will allow the development of new case studies and affirmation and improvement of existing operational applications. Scientifically, new coastal and ocean applications may arise and existing ones may be improved, particularly when used synergistically with other ocean sensors. The degree of interest in spaceborne SAR may be judged from the significant participation in the 3rd ERS Symposium [ESA, 1997] and the recent special issue of the Journal of Geophysical Research Oceans concerning ERS results [Johannessen et al., 1998]. In that special issue, many of the SAR papers considered the accuracy and role of wind field information estimated from SAR image data. Beyond this, the now 7-year archive of SAR data will be lengthened through the ENVISAT-1 and RADARSAT-2 timeframes, allowing inter-decadal study of coastal change at finer resolutions than are available from current ocean monitoring sensors.

6. Ice Sheets and Glaciers

Ice sheets and glaciers have a pivotal position in our studies of the global climate system. They provide an important record of climate history and an excellent target for detection of modern climate change. Although the size of the ice sheets' current contributions to measured sea level rise is not yet known, we do know that past contributions were large, and that the potential exists for accelerated contributions in the future, with major potential impact on human activities in coastal areas.

Satellite remote sensing is revolutionizing this branch of climate science by empowering glaciologists with instruments capable of collecting spatially extensive, yet detailed, data sets of critical parameters. With the help of these new techniques, scientists have begun to address key science issues, which include:

1) The use of ice sheets and glaciers as indicators of current climate, providing valuable extensions to climatic monitoring networks.

2) The understanding of the role of ice sheets and glaciers in the atmospheric and oceanic circulations.

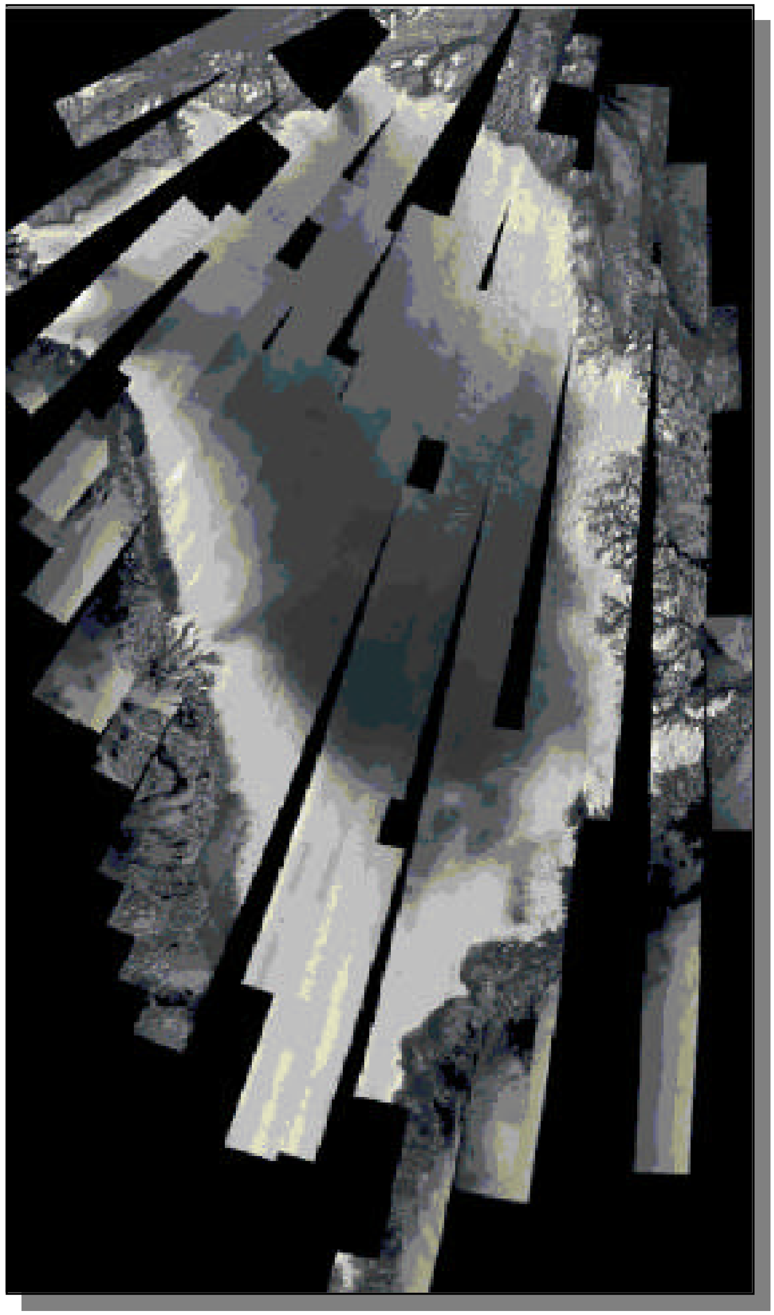
3) The current mass balance of polar ice sheets and glaciers, and what is driving their contributions to sea level rise. Estimates of present mass balance are poorly constrained – a notable weakness in present estimates of mass balance is that they fail to add up to the present rate of sea level change, even when liberal error estimates and other contributing effects are included. Predictions of future sea level change must be tempered until we better understand the current mass balance of the existing ice, and the ice dynamics and climatic interactions which determine it.

4) The controls on ice flow and the potential for inherent instabilities in ice flow that could lead to dramatic changes in the dynamics of existing glaciers or ice sheets. This topic is relevant to global climate through the effect altered ice flow would have on ice volume and, by direct connection, sea level.

SAR can significantly contribute to answering these key questions. SAR provides the obvious benefits of a weather-independent, day/night imaging system, which are crucial in the ice-sheet and glacier environments where persistent clouds continue to hamper data acquisitions by visible imagers and where the polar night imposes a prolonged period of darkness. In addition, unlike visible imagers, radar penetrates the snow surface, a property which provides glaciologists with the capability to sense snow conditions on an ice sheet or glacier. Before ERS-1 was launched, limited SAR data of ice sheets only hinted at the potential uses of SAR for studying ice sheets and glaciers. ERS-1 data have allowed this potential to be proven and have expanded the potential uses of SAR to even broader horizons. It is through the use of this type of tool that we may be able to quantify the role of the ice sheets in the present climate, and begin to get a handle on methods for predicting future impacts.

ERS-1 SAR has been successful at mapping the melt zones of glaciers and ice sheets (Figure 6.1) and monitoring their temporal evolution across several seasonal cycles. This unique capability provides a new basis for monitoring the effect of climate variability over the broad expanse of ice sheets.

FIGURE 6.1



ERS-1 SAR Mosaic of the Greenland Ice Sheet. The dark (low backscatter) area in the center of the ice sheet does not melt, and so has a relatively fine grained, moderately layered snowpack. The bright areas surrounding the center are where the refreezing of water from surface melting produces rough scatterers within the snowpack. This is one of the regionally brightest backscattering areas on Earth. The narrow band of lower backscatter surrounding the bright area is bare ice exposed by summer melt-off of the overlying snow.

SAR imagery copyright ESA 1993. Mosaic produced by Ron Kwok (JPL) and Mark Fahnestock (UMCP).

RADARSAT-1 SAR recently mapped Antarctica at a resolution that is 30 times finer than the previously available comprehensive optical coverage (cover Figure). This imagery opens large areas of Antarctica to new research efforts, and has already provided a picture of ice flow that is unexpectedly complex.

ERS-1 SAR has provided critical observations of iceberg production, a quantity that is useful for determining the mass balance of ice sheets, and of surface morphological features such as streams, lakes, ice margin positions, and crevassed areas in great detail, thereby opening the door to monitoring their evolution.

An even more profound breakthrough has been the wide utilization of ERS SAR interferometry to measure ice velocity, ice sheet topography and grounding line position at an unprecedented level of spatial detail and precision (Figure 6.2). This unforeseen capability has redefined what can be measured; it has altered the course of many studies of ice sheet motion.

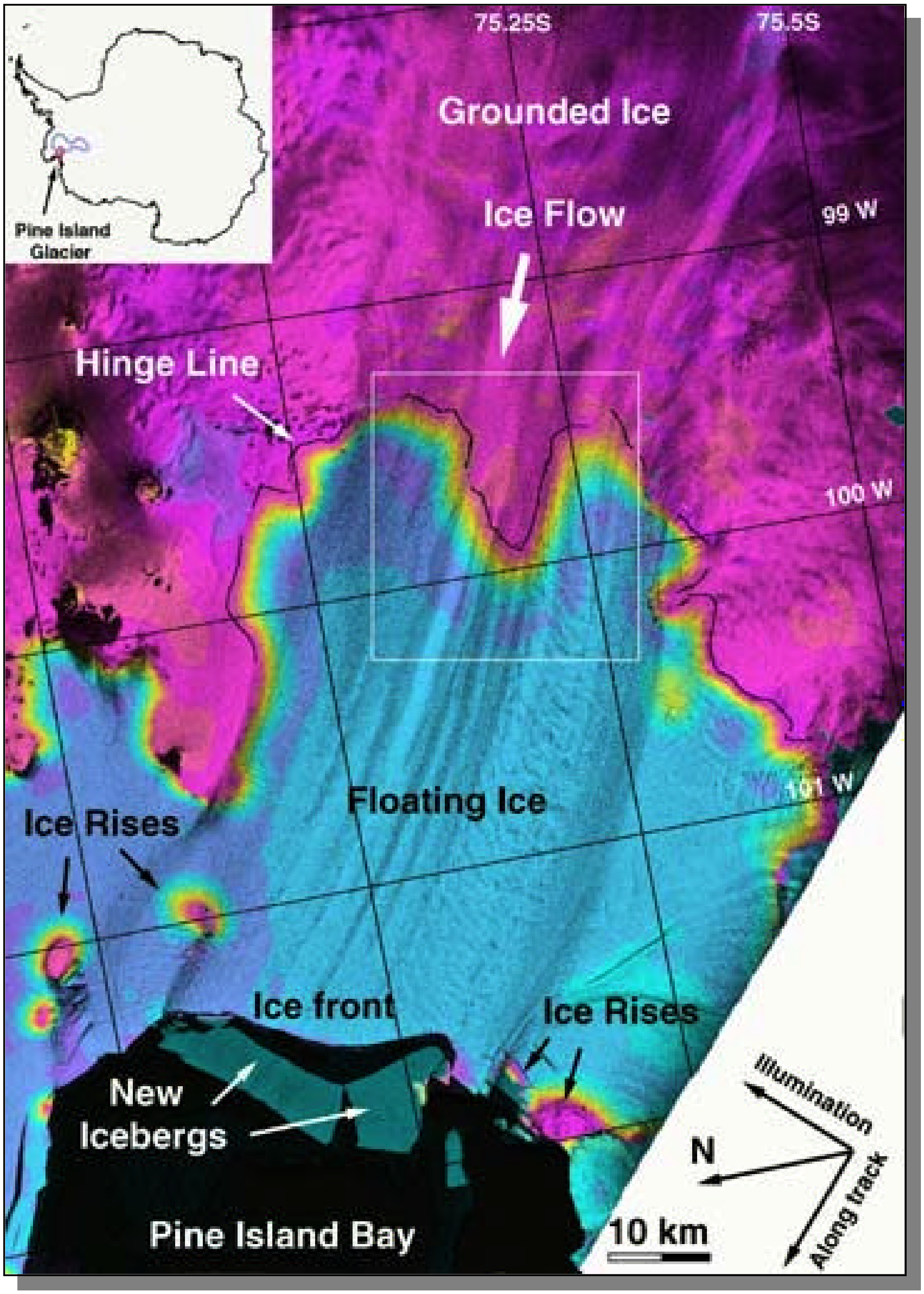
In a few short years, SAR has lead to a number of discoveries on the large ice sheets, including the presence of unexpected, large ice streams in both Antarctica and Greenland, and detection of rapid changes in both discharge glacier speed and grounding line position of major outlet glaciers controlling the flow of ice into the world's oceans.

The comprehensive record of the ice sheets which began with ERS-1 in 1991 has laid the foundation for the detection of change related to climatic variation. Continuous SAR coverage of ice sheets and glaciers holds potential for extraordinary glaciological returns. Never before have we had the availability of such a detailed historic data set against which we can measure change. SAR is revolutionizing the study of ice sheets, making it possible to detect subtle changes in ice sheet margins and flow patterns that might be expected in response to changing climate. Modern awareness of the climatic importance of the polar regions must be expressed in the ability of new sensors to extend their view to the poles. Pursuit of this critical effort needs to be supported into the next century using data collected by ENVISAT-1, RADARSAT-2 and ALOS.

ENVISAT-1 and RADARSAT-2 will extend the 8-year ERS/RADARSAT data record at C-band (6 cm) frequency to allow detection of ice sheet changes over decadal time scales, which is unprecedented. The added multi-polarization and wider swath capabilities of these instruments will enhance our knowledge of the hydrologic and climatic regimes of ice sheets and glaciers and provide a more comprehensive and systematic coverage of rapidly evolving regions from the coast all the way to the deep interior. The Japanese ALOS L-band multi-polarization SAR system will provide additional capabilities for this research, enhanced by a radar frequency selection which has great promise for interferometric glaciological applications.

Without continued access to SAR coverage of glaciers and ice sheets, glaciology and related climate research will be blind to the evolution of this system, and will have lost access to tools that are on their way to becoming as fundamental to the science as ground surveying equipment was thirty years ago.

FIGURE 6.2



ERS radar interferometry observations of Pine Island Glacier, Antarctica, were employed to map the location of its grounding line (junction with the ocean waters, shown here as a black continuous line separating grounded ice (purple) from floating ice (blue)). The grounding line of this major ice stream retreated 5 km between 1992 and 1996, which means that the ice is thinning at 3.5 m/yr. [Rignot, 1998]. Because of the important implications of this retreat for the future of the West Antarctic Ice Sheet, it is essential to extend the monitoring of its evolution over the next decades.

7. Sea Ice

Interactions between sea-ice, ocean and atmosphere in the polar regions strongly affect the Earth's climate. Sea ice growth, movement and decay affect the energy and mass balance of the polar ocean system. Surface heat and brine fluxes associated with sea-ice growth contribute significantly by destabilizing the mixed layer and by initiating open-ocean convection in a few key locations, thereby regulating the fundamental water-mass modification processes which drive ocean thermohaline circulation. Snow covered sea-ice reflects most of the incident solar radiation back into space, while freshwater fluxes associated with ice melt serve as stabilizing elements in the thermohaline circulation of the North Atlantic and Southern Ocean. Processes taking place along the sea-ice margin and in narrow continental shelf regions of coastal seas actively control rates of water-mass formation, upwelling, convection, and sediment transport.

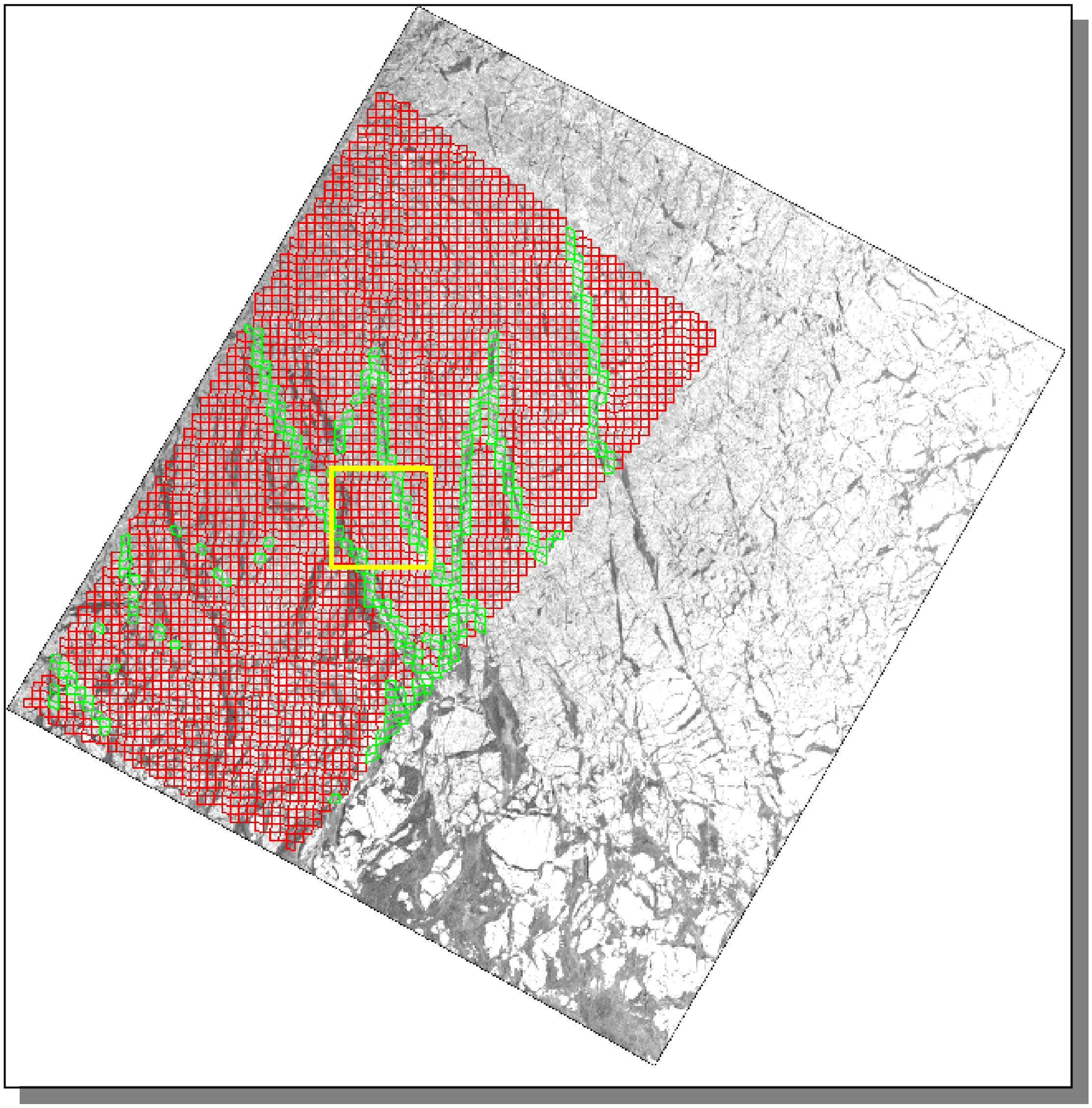
Net ice melt occurs in the Greenland Sea where sea ice drifting out of the Arctic basin through the Fram Strait encounters warmer North Atlantic water. It appears that convection in the Greenland and Iceland Seas is conditioned by freshwater export from the Arctic Ocean. The melt process is essential in maintaining the stratification of the ocean in this area, thus preventing significant overturning. Overturning and deep convection are important in the formation of deep water and the maintenance of the global thermohaline circulation [Aagaard and Carmack, 1989].

Changes in the Arctic climate system appear to be occurring, beginning in the late 1980s. These changes include: the recent decrease in the sea-level pressure in the Arctic [Walsh et al., 1996]; a late spring-early summer warming observed in the late 1980s and early 1990s; an enhanced melt-back of the summer ice, especially during 1990, 1993 and 1995; the recent increase in the length of the Arctic melt season [Smith, 1998]; freshening of the Arctic mixed layer [McPhee et al., 1998]; and a change in the Arctic Ocean circulation [Morison et al., 1997]. In contrast to this apparent Arctic warming, there are observations from many sources of a regional cooling in the Labrador Sea.

Significant changes have also been noted in Southern Ocean regional characteristics. In particular, these are reflected in a consistent, long-term warming of both Weddell Deep Water and Weddell Sea Bottom Water masses over the period October 1989 to May 1996. Although the interannual variability in bottom-water outflow is significant, an increase of 0.06 degrees in Antarctic Bottom Water has occurred in conjunction with warming of Weddell Deep Water. This suggests a strongly reduced production of cold source waters and/or an increase in the magnitude of the inflow of Circumpolar Deep Water into the Weddell Gyre circulation by warm core eddy shedding from the Antarctic Circumpolar Current.

Understanding and modelling these phenomena require large-scale, long term monitoring of the changes in the ice cover, including: sea-ice motion, thickness, and concentration. Many of these important climate variables can be directly measured with regular SAR coverage of the polar oceans. Feature tracking in sequential SAR images reveals the motion and fracturing of the ice (Figure 7.1); radiometric analysis gives the ice concentration and extent; changes in the SAR backscatter can be used to infer melt onset in the spring and freeze-up in the fall, from which the length of the melt season is derived. Another application of sea-ice motion is monitoring the transport of sediments and radioactive waste, which are entrained into newly forming ice in the shallow marginal seas north of Siberia.

FIGURE 7.1



RADARSAT ScanSAR Wide B image of sea ice in the Beaufort Sea, January 11, 1998. The colored grid, computed by the RGPS, shows how the ice has deformed since the previous day. Red grid cells have remained square or rigid; green grid cells have undergone significant distortion due to relative motion of the ice cover along linear fractures or leads. The 60 x 60 km yellow square is centered on the SHEBA ice station.

Spaceborne imaging radar is particularly suited to the mapping of the polar regions because it is unaffected by clouds and darkness. Visible and near-IR remote sensing of the surface are adversely affected by summer cloud cover and extended winter darkness. Current imaging radars allow us to resolve individual leads and floes, in which each 100-meter pixel can be identified with a single surface type, whereas passive microwave sensors have only been enable to provide a rather low resolution view of the sea ice cover, in which the footprint of the sensor encompasses a mixture of surface types. Since 1978, synthetic aperture radars (Seasat, ERS-1, and ERS-2) have provided the sea ice community with snapshots of the ice cover. The narrow swaths (100 km) of these sensors and limited data availability, however, hampered the large-scale use of these datasets for scientific investigations. Nevertheless, it was demonstrated that fields of ice motion and ice type can be routinely generated [Kwok et al., 1990; Drinkwater, 1998a,b]. A Geophysical Processor System (GPS) was installed at the Alaska SAR Facility shortly after the launch of ERS-1 (1991), and this system routinely provided ice motion and ice type products during its three years of operation.

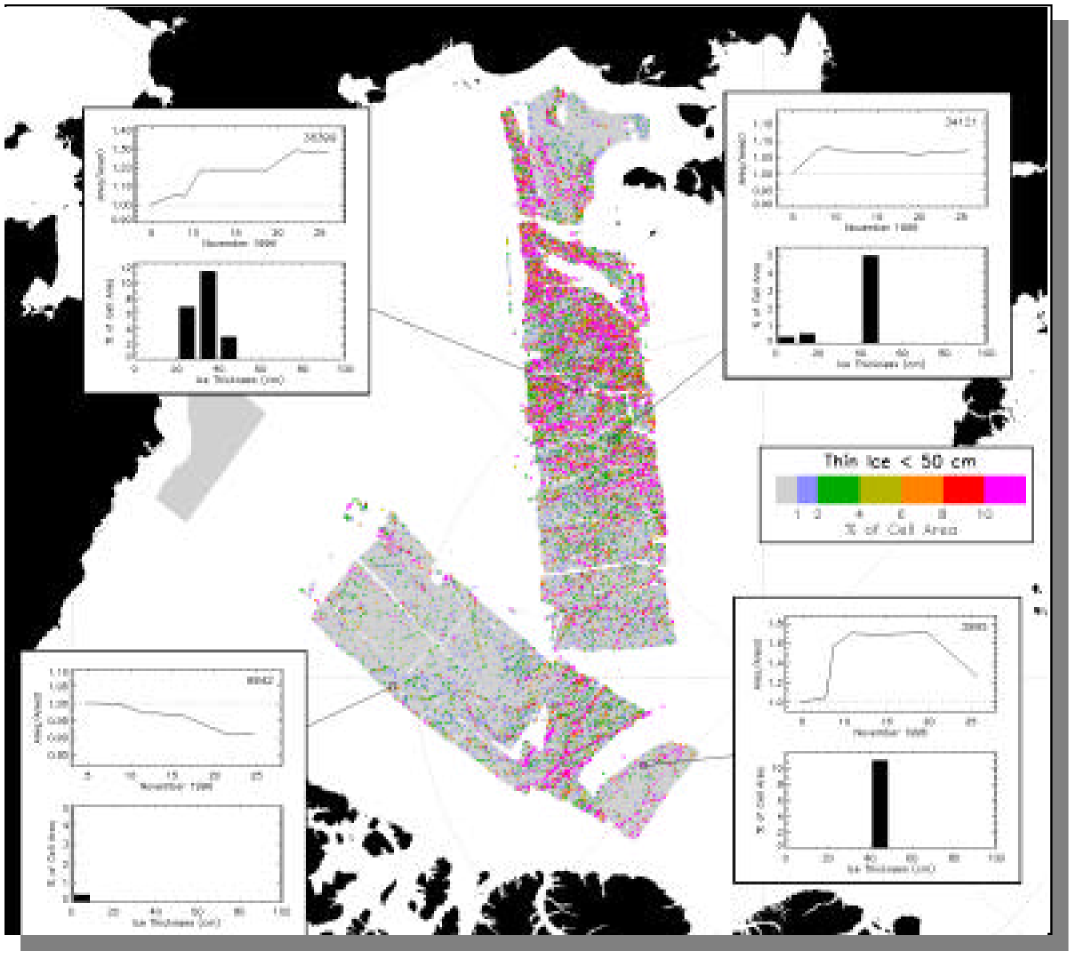
RADARSAT-1 now provides high resolution imagery of the entire Arctic Ocean every three days (the "Arctic Snapshot"). These data have been collected and archived at the Alaska SAR Facility since November 1996. A RADARSAT Geophysical Processor System (RGPS) has been developed to process the image data into fields of geophysical variables. The following datasets will be produced on a 10-km grid at weekly intervals: sea-ice motion, sea-ice age, sea-ice thickness of young ice, sea-ice deformation, open water fraction, and (twice / year) dates of melt onset and freeze-up. No other automated processing system has ever ingested such an enormous volume of image data for the purpose of creating higher-level geophysical products.

An example of an ice thickness map is shown in Figure 7.2. These analyzed maps from the RGPS provide a view of the characteristics of the ice cover that is unprecedented in its detail. We are more than half way through the expected life span of RADARSAT-1. It is essential to maintain a long-term program to extend the SAR record for monitoring the seasonal, interannual and decadal variability of the ice cover. Furthermore, it is essential to further exploit existing tools, developed as part of the RGPS, on as wide a variety of SAR datasets as possible in order to satisfy this goal in both hemispheres.

ENVISAT-1 and RADARSAT-2 provide two opportunities to maintain an uninterrupted SAR measurement program in support of global change research of the polar regions. Both sensors provide wide-swath modes capable of mapping the polar oceans in less than a week. The dual polarization offered by these radars allows us to unambiguously map additional parameters of the ice cover which are more difficult to recover using single polarization radars [Rignot and Drinkwater, 1994]. It has been shown [Winebrenner et al., 1995; Kwok et al., 1995] that polarization ratios are positive discriminators of water and ice, and can potentially allow the direct measurement of thin ice thickness. These radar channels will provide an enhancement of our measurement suite, giving us more accurate mapping of the critical thin-ice end of the sea-ice distribution.

A much needed capability is the mapping of the Southern Ocean sea-ice cover. In particular, no complete seasonal or annual cycle exists for any part of the Southern Ocean due to the logistical difficulties of data reception and return data shipping. Many locations around Antarctica remain unimaged by high-resolution ERS or RADARSAT SAR. The data shipping challenge requires some solution to high data-rate communications in order to return SAR data received at Antarctic stations such as McMurdo. A further possibility is the Ku-band satellite transmission link (ARTEMIS) for ENVISAT-1 which will allow the study of regions without direct downlink to a local Antarctic receiving station. This will allow data reception in large parts of East Antarctica which remain poorly covered by ERS and RADARSAT SAR.

FIGURE 7.2



Thin ice distribution along two RADARSAT swaths, November 1996, computed by RGPS. For four selected grid cells, the cell area history and ice thickness distributions are shown.

SAR is the only instrument able to characterize the small-scale deformation of the sea-ice cover in response to wind and tidal influences. Tidal influence is of particular bearing in the Southern Ocean, where primary bottom water production sites are located in regions of intense tidal shear activity. SAR can also capture the short term variability of the sea-ice response to wind and current forcing. Ultimately, with the new mapping tools provided by technologies such as the RGPS, an "Antarctic Snapshot" could be implemented to provide the same Antarctic processing capability as we have done in the Arctic. This capability could be implemented with the lower-resolution global monitoring mode of ENVISAT-1 (1 km resolution; 400 km-wide swath), in order to provide large-scale ice motion products from data which do not require reception in Antarctica.

The attributes of ENVISAT-1 and RADARSAT-2 for large-scale and small-scale coverage pay large dividends in comparison with prior SAR sensors. In particular, unambiguously identifying thin ice areas is very important. But the commitment to provide global, low-resolution coverage with ENVISAT-1 certainly warrants significant interest from the perspective of developing a bi-polar record of global sea-ice variations in response to climate variability.

8. Operational Applications

For the operational community, the most important scientific question related to SAR is: which of the possible geophysical measurements that can be made with SAR are of practical use for environmental monitoring and prediction? This involves development of parameter extraction algorithms (e.g., ice type and wind speed), validation of their accuracy, inclusion of the algorithms in an operational software system, and an assessment of the usefulness of the SAR measurements to ongoing operational activities given the accuracy characteristics, areal coverage, timeliness of the data, and observation repeat frequency.

SAR remote-sensing instruments provide unique environmental information, quite different from, yet complementary to passive systems such as visible, infrared and passive microwave radiometers. As active instruments, they provide their own illumination, which is minimally affected by weather conditions and time of day or night. This is particularly important in regions with persistent cloud cover, such as the polar regions. SAR instruments are sensitive to surface roughness, especially the capillary and small gravity ocean surface waves of the order of the radar wavelength, and to changes in dielectric constant. Man-made targets such as buildings and ships are excellent radar reflectors and are quite evident in SAR images. In addition, the synthetic aperture technique of image formation and the SAR system characteristics provide very high resolution imagery (in the 10 to 100 meter range), one to two orders of magnitude better than current operational infrared sensors like the AVHRR. These characteristics of SAR data make them extraordinarily useful for many operational monitoring activities.

Additional wide-swath instruments such as ENVISAT-1 ASAR, RADARSAT-2, and ALOS will be important for operational applications such as:

1) Sea and lake ice monitoring - For ice monitoring, SAR is the remote sensing instrument of choice for its all-weather, day / night, and high resolution characteristics, as well as its ability to distinguish between ice types. Currently, the U.S. National Ice Center makes extensive operational use of RADARSAT-1 SAR ice imagery in the Arctic, in the seas surrounding Alaska, and in the Great Lakes [Bertoia et al., 1998].

2) Iceberg detection - The International Ice Patrol uses spaceborne SAR to target areas containing icebergs for closer inspection with aircraft.

3) River ice jam monitoring - For the past two years, the Alaska River Forecast Center in Anchorage has used SAR imagery of the larger Alaskan rivers to monitor spring breakup and flooding from river ice jams [Lunsford, 1998].

4) Fishing enforcement - The ability of SAR to detect ship signatures and evidence of fishing activity is very promising. Studies are being conducted in the Bering Sea to assess the ability of SAR to monitor the pollock fishery there [Montgomery et al., 1998]. Near real-time imagery was provided during April and May, 1998 to the Alaska Department of Fish and Game to help manage the herring roe fishery in Bristol Bay, Alaska (see Figure 8.1).

FIGURE 8.1

This RADARSAT-1 Standard Mode image from May 14, 1998 shows large processing vessels and small fishing vessels near Hagemeister Island in Bristol Bay, Alaska. The small vessels are harvesting herring roe from kelp beds. (Figure courtesy of Pablo Clemente-Colón of NOAA/NESDIS)

5) Oil spill detection - The sensitivity of SAR to capillary waves and short gravity waves makes it sensitive to dampening of these waves by natural or man-made oils on the ocean's surface. SAR imagery has been obtained to support NOAA's Hazardous Materials response efforts for major oil spills, and Cook Inlet / Prince William Sound SAR imagery are being routinely inspected for indications of spills associated with oil production and transportation activities.

6) Winds and storms - Work is underway to develop high-resolution wind field estimates from SAR to complement scatterometer winds in coastal areas as input to high-resolution weather and ocean current models and oil spill trajectory models [Beal

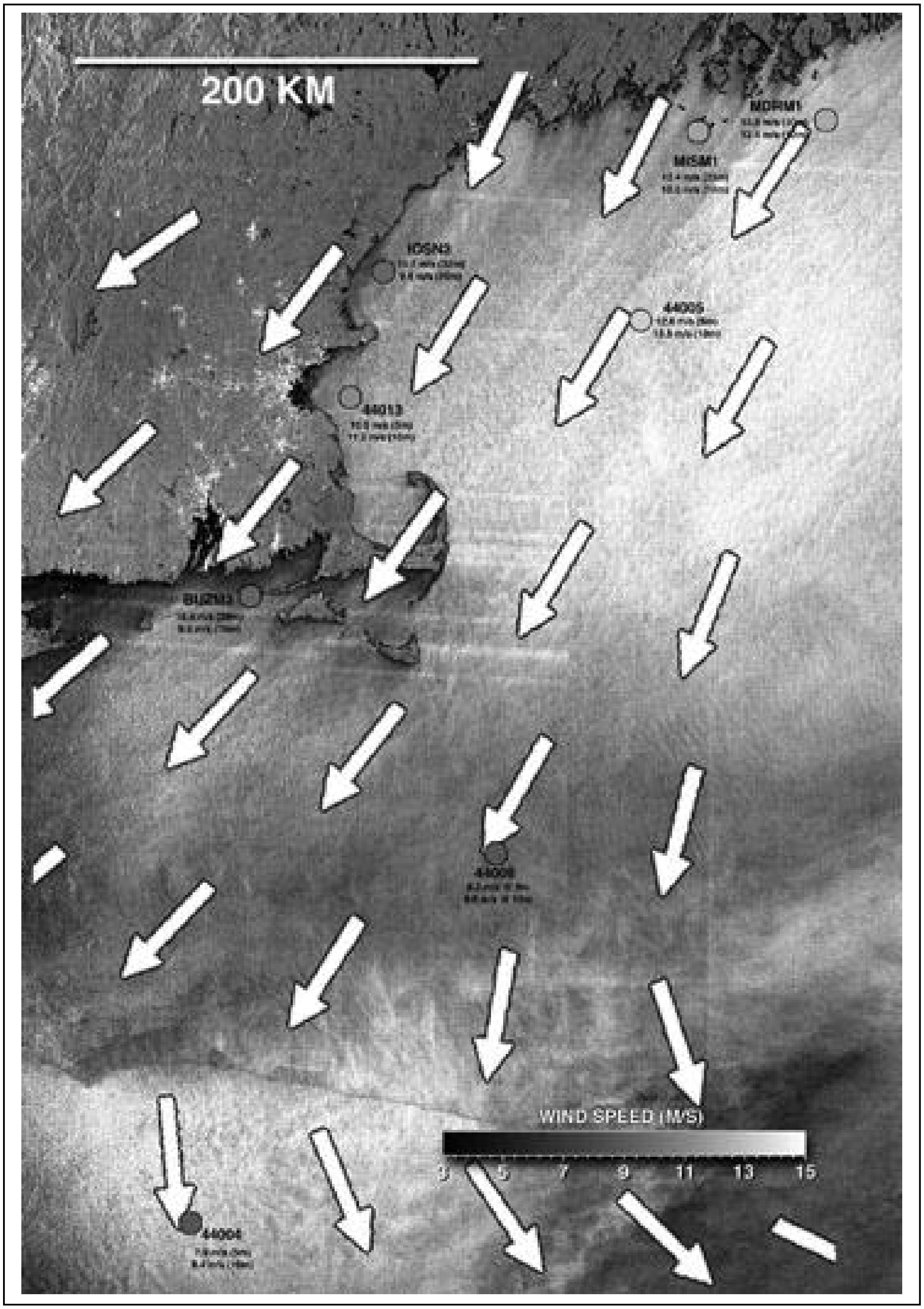
and Pichel, 1998] (Figure 8.2.). These wind measurements will also be useful in studying the fine structure of storms. One potential operational application of SAR for meteorology is to monitor the location and severity of polar low pressure systems. SAR data can be used to locate the storm's center and to measure the wind field within and around these potentially dangerous storms, providing valuable data concerning the storm's structure at the sea surface. (See Figure 5.2).

7) Flood mapping - The Federal Emergency Management Agency is making operational use of SAR data in the mapping of flooded areas along rivers and in coastal areas.

8) Other applications - Other potential operational applications of SAR imagery include wave spectra measurement; location of ocean features such as fronts, currents, and eddies; the measurement of mixed layer depth using internal waves; monitoring of glacier-dammed lakes; coastline mapping and change detection; and mapping wetland use and change [Interagency Ad Hoc Working Group on SAR, 1996].

Geographic coverage, temporal coverage, the life span of the data source, and timeliness of data delivery are important factors in deciding whether or not a particular data source is truly useful for operational environmental monitoring applications. Currently, RADARSAT-1 is the only wide-swath SAR instrument available, although ERS-2 and to some extent JERS-1 are available as narrow-swath alternatives. Additional wide-swath instruments such as ENVISAT-1 ASAR and RADARSAT-2 will be important for operational applications because they will provide redundancy in case of failure of RADARSAT-1, additional geographic coverage, and greater coverage frequency. These upcoming instruments will also provide the assurance that since this data source will be available for the foreseeable future, it is worth the continuing expenditure of resources to develop and implement operational systems to utilize these data. For example, without at least daily coverage of the Bering Sea, something that is not possible from RADARSAT-1 alone, it may not be operationally useful to monitor polar lows with SAR. Also, the calculation of ice motion south of the Arctic Circle is difficult without greater temporal coverage than that provided by RADARSAT-1 alone. Continued SAR data availability will assure that investment in operational ice algorithms, including an automated global sea ice product, will continue [Partington and Steffen, 1998]. The dual-polarization characteristics of ENVISAT-1 ASAR will be useful in improving ice type discrimination, and possibly in the discrimination of oil spills and natural slicks [Apel and Carsey, 1995].

FIGURE 8.2



Wind speed image derived from RADARSAT-1 ScanSAR Wide B image on November 22, 1997 at 22:31 UT. The coastline shown stretches from Long Island, New York to Maine. The greyscale indicates wind speed in meters/sec. The arrows are the FNMOC model wind field direction for November 23, 00:00 UT. Circles are the NOAA moored buoy wind measurements with the shade within the circle indicating the wind speed using the same greyscale as for the SAR wind image. (Figure courtesy of Robert Beal, Donald Thompson, and Frank Monaldo of the Johns Hopkins University Applied Physics Laboratory).

Table of Spaceborne Synthetic Aperture Radars

PLATFORM	NATION	LAUNCH	BAND[1]/POL[2]	RECORDER[3]	LIFETIME	STATUS
Seasat	USA	1978	L / HH	No	3 months	Ended
Shuttle (SIR-A)	USA	1981	L / HH	Yes	2 days	Ended
Shuttle (SIR-B)	USA	1984	L / HH	Yes	8 days	Ended
Kosmos 1870	USSR	1987	S / HH	Yes	2 years	Ended
ALMAZ	USSR	1991	S / HH	Yes	1.5 years	Ended
ERS-1	Europe	1991	C / VV	No	2-3 years	Standby
JERS-1	Japan	1992	L / HH	Yes	2 years	Operational
Shuttle (SIR-C/X-SAR)	USA	April 1994	L,C / quad and X / VV	Yes	10 days	Ended
Shuttle (SIR-C/X-SAR)	USA	October 1994	L,C / quad and X / VV	Yes	10 days	Ended
ERS-2	Europe	1995	C / VV	No	2-3 years	Operational
RADARSAT-1	Canada	1995	C / HH	Yes	5 years	Operational
Shuttle (SRTM)	USA	1999	C / HH, VV[4] and X / VV	Yes	11 days	Launch Scheduled
ENVISAT-1	Europe	2000	C / dual	Yes	5 years	Launch Scheduled
RADARSAT-2	Canada	2001	C / quad	Yes	5 years	Approved
LightSAR	USA	2002	L / quad	Yes	5 years	Approved
ALOS	Japan	2003	L / dual	Yes	5 years	Approved

Notes:
1. X band (3.1 cm); C band (5.66 cm); S band (10.0 cm); L band (23.5 cm).
2. Polarization: dual means two of HH, HV, VH, VV; quad means all four.
3. On-board recorder allows data to be collected outside of fixed station masks.
4. Polarization will be alternating swaths of HH and VV.

For more detailed information, please refer to the book:
Principles and Applications of Imaging Radar, Manual of Remote Sensing, 3rd Edition, F. Henderson and A. Lewis, Editors, John Wiley and Sons, (June 1998 scheduled publication).

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List of Acronyms

ADRO	Application Development and Research Opportunity
AIRSAR	Airborne Synthetic Aperture Radar
ALOS	Advanced Land Observing Satellite
ASAR	Advanced SAR
ASF	Alaska SAR Facility
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
AVHRR	Advanced Very High Resolution Radiometer
CEOS	Committee on Earth Observing Systems
CSA	Canadian Space Agency
EOS	Earth Observing System
ERS	European Remote-Sensing Satellite
ESA	European Space Agency
ESE	Earth Science Enterprise, a NASA program
FNMOC	Fleet Numerical Meteorology and Oceanography Center
GBFM	Global Boreal Forest Mapping
GCM	General Circulation Model
GPS	Global Positioning System / Geophysical Processor System
GRFM	Global Rain Forest Mapping
InSAR	Interferometric SAR
LBA	Large-scale Biosphere-Atmosphere
MTPE	Mission to Planet Earth, now called ESE
NASDA	National Space Development Agency of Japan
NOAA	National Oceanic and Atmospheric Administration
RGPS	RADARSAT Geophysical Processor System
SAR	Synthetic Aperture Radar
SIR	Shuttle Imaging Radar
SRTM	Shuttle Radar Topography Mission
TOPSAR	Topographic SAR

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