Antarctic Science 2 (2):105–121 (1990)

Remote sensing in Antarctica and the Southern Ocean: applications and developments

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Abstract: Remote sensing provides the means to study features and processes that are not easily accessible or amenable to direct observations. The polar regions, and Antarctica in particular, offer a variety of examples where the ability to observe from afar is necessary or highly desirable. In particular, studies of ice shelf processes, changes in the sea-ice cover, and ice-ocean-atmosphere investigations must rely in large part on measurements from aircraft and satellites. The polar regions present a unique set of problems that complicate applications and limit the usefulness of certain sensors; new instruments planned for launch in the 1990s will help resolve many of these difficulties. Examples of remote sensing applications for the study of the continent, drifting ice, ocean, and atmosphere demonstrate ways that existing data as well as new observations can be used to aid polar research.

Accepted 30 March 1990

Key words: satellites, glaciology, climatology

Introduction

The value of remote sensing techniques in the polar regions is determined by a combination of factors unique to the poles. These include the polar "night", physical characteristics including climatic extremes and interactions, inaccessibility, environmental sensitivity, and natural resources. These factors are obviously intertwined; if the polar regions were of little interest for climate and biological studies or for resource exploration, problems of access and environmental sensitivity would be less critical, and the need for accurate, continuous monitoring and observations would therefore be of less concern. Modelling studies suggest that they may be particularly sensitive to greenhouse warming and, given the rapidity with which snow and ice cover can respond to climate, one could logically assume that monitoring of polar conditions might provide early evidence of global climate change. The polar regions, and Antarctica in particular, also serve as laboratories for the study of unique habitats, both on land and in the sea. In some cases, biological studies can be conducted using remote sensing techniques. In other cases, support of such studies can benefit from remote sensing for siting, baseline mapping, and logistics. In short, all the reasons for using remote sensing technology in the lower latitudes exist for the polar regions. These reasons are, in fact, sharpened and enhanced due to the unique qualities of Antarctica.

The objectives of this review are to provide a sampling of remote sensing and remote sensing related activities in Antarctica and the Southern Ocean, and to touch upon some potential new ways that remote sensing can contribute to studies in high latitudes. Emphasis is placed on remote sensing of features unique to Antarctica or to the polar regions. Some applications are treated in more detail than others. This emphasis is not meant to indicate the importance of particular research areas, but arises from the desire to treat at least some topics in enough detail to be of value. Satellite applications are given greater emphasis than are aircraft and surface observations since spaceborne sensors and techniques are undergoing the most rapid expansion and change. Prior to presenting details on specific applications, it is worth summarizing the basic contributions of remote sensing to Antarctic research.

Studies of sea ice extent and concentration on all but local scales, and interactions between the ocean, atmosphere, and ice cover, rely on remotely sensed data. In particular, spaceborne passive microwave sensors beginning with the Electrically Scanning Microwave Radiometer (ESMR) on board Nimbus 5, followed by the Seasat Scanning Multichannel Microwave Radiometer (SMMR), Nimbus 7 SMMR, and the Special Sensor Microwave/Imager (SSM/I) carried on the Defense Meteorological Satellite Program (DMSP) platform, provide complete coverage of the Antarctic sea ice, and nearly complete coverage of the Arctic ice pack. The Japanese Marine Observation Satellite (MOS-1) carries a passive microwave radiometer, as well as medium and high resolution visible and thermal wavelength imagers. Although designed for open-ocean applications, the synthetic aperture radar (SAR) on board Seasat demonstrated the ability of a satellite SAR to collect detailed information of ice structure and motion in addition to ocean surface characteristics. Ice sheet thickness can be measured directly using airborne radio echo sounding, or inferred from changes in surface elevation as measured by spaceborne radar and laser altimeters.

Medium resolution visible and thermal wavelength sensors such as those on board polar-orbiting meteorological satellites (e.g., the NOAA Advanced Very High Resolution Radiometer [AVHRR] and the Defense Meteorological Satellite Program [DMSP] Optical Line Scan system), and high resolution instruments like Landsat and SPOT provide comparable sea-ice information, but are limited by cloud cover and the polar "night". When viewing conditions permit, both medium and high resolution sensors can provide a wealth of information about surface conditions on the Antarctic ice sheet and ice margin, including flow patterns, surface albedo, temperature and roughness, blue ice, ice sheet calving, and ice berg distribution.

Although complicated by a variety of factors unique to the poles, satellite observations are the only means to acquire a generally consistent climatology of polar cloud cover. A reliable cloud climatology for Antarctica that spans several years is lacking, even though such climatologies are needed for model validation. Derivation of such a climatology from digital imagery, as well as extraction of atmospheric profiles of water vapour and temperature from sounder data in the polar regions, are active research areas. Incoming solar energy and outgoing longwave radiation have been monitored by a series of earth radiation budget sensors. Ozone depletion and other aspects of the chemistry of the upper atmosphere have been observed by a comparable set of instruments, including the Nimbus 7 Stratospheric and Mesospheric Sounder (SAMS), Limb Infrared Monitor of the Stratosphere (LIMS), and the Solar Backscatter Ultraviolet/Total Ozone Mapping Spectrometer (SBUV/TOMS), and the NOAA SBUV. Over the open oceans sea surface temperatures and ocean colour are routinely estimated from satellite data, and sea surface height, surface wind speed, and wind direction can be observed using altimeters, microwave imagers, and microwave scatterometers. A variety of other remote sensing research and applications exist with potential applications in Antarctica. Although mineral exploration using remote sensing techniques is unlikely in the Antarctic, remote sensing in support of shipping and monitoring of human activities and impacts may become a key aspect of environmental protection of the Southern Ocean and coastal habitats.

In the following sections, the research categories mentioned above are discussed in more detail, preceded by some background on remote sensing characteristics unique to the polar regions.

Remote sensing considerations in high latitudes

Remote sensing in Antarctica is complicated by several factors. These include extended periods of winter darkness, extensive cloud cover in some areas, low-level temperature inversions, and high-albedo surfaces that can saturate visible wavelength sensors (Hall & Martinec 1985, Dowdeswell & McIntyre 1986). However, in spite of the limits placed on them by the polar regions, visible and thermal wavelength sensors are of great value when observing conditions are suitable. Geostationary orbits that permit nearly continuous viewing at low and mid latitudes are of little use for the poles, but near polar orbits provide frequent coverage over polar regions due to convergence of the orbit crossings at high latitudes. Even with these orbits, poleward coverage may not be complete; Seasat SAR data extend only to 72° latitude and Landsat coverage reaches to 81°. Nimbus 7 SMMR leaves about a 6° gap at the poles, while the area not covered by SSM/I is 2.4°. Imaging systems that scan across a particularly wide swath of the earth's surface, such as AVHRR with a swath width of 2580 km, provide complete coverage over the poles. By the end of the decade, selected coverages acquired at high resolution will exist for nearly a 30 year period; long enough to begin identifying climatic trends. Landsat was first launched in 1972, the Soviet Soyuzkarta system in 1976, and the French SPOT in 1986. Archives of these data are available for the Antarctic in both digital and hardcopy form (National Science Foundation 1989*a*). Due to their insensitivity to lighting conditions and relative insensitivity to weather, microwave sensors are particularly applicable to Antarctic studies. The physical properties of ice and snow as well as the scales of processes in the polar regions make passive microwave data particularly useful for climate studies. When more detailed observations are required, active microwave (radar) sensing is appropriate, although a substantial penalty must be paid in terms of processing complexities (for SAR), data volume, and satellite power requirements.

Research applications

Ice sheets and ice shelves

Remote sensing studies of the Antarctic ice sheets and ice shelves are primarily concerned with the mass balance of the ice cover, in terms of ice sheet flow, positions of the ice margins, distributions of ice thickness, and accumulation or ablation of the ice sheet. In some cases, remote sensing provides information on such basic measures as extent and thickness. In other examples, remote sensing is used to study flow patterns, sub-surface structure, surface albedo, and surface temperature.

Direct measurements of ice thickness and variations of structure within ice masses are provided by radio echo sounding (RES) which, due to system design requirements, have been limited to surface and aircraft platforms. Prior to the development of RES, conventional seismic techniques and gravity measurements were used to map ice thickness. RES uses a downward-looking pulsed radar system to penetrate the ice (Drewry 1981). The Antarctic ice sheet in particular, due to its sub-zero temperatures, is well suited to electromagnetic sounding. In addition to ice thickness and layering, RES provides information on sub-ice water and sub-ice geology/geophysics. Depending on the application, RES systems are designed to weigh vertical resolution against deep penetration. RES-derived observations of the changing structure in the ice sheet may reflect seasonal variations in snowfall or temperature. Below about 100 m, ice reaches a constant density; changes in reflectivity may be due to acid impurities or other atmospheric pollutants. The ability of RES to map ice structure and bedrock surfaces can be combined to study the effects of sub-glacial peaks on the flow of ice sheets (Robin & Miller 1982).

Ice shelf thickness can also be inferred by mapping ice sheet elevation and topography using radar and laser altimetry. Altimetry measurements show ice drainage features and, with successive overflights spanning several years, could detect thinning or thickening of the ice sheet. A measurement accuracy of ± 1 m of elevation should make it possible to determine ice thickness within 10 m (Robin *et al.* 1983). Radar altimeters have been carried onboard Seasat, GOES-3, and Geosat, and are planned for several new satellites to be launched in this decade. As noted earlier, Seasat acquired range data between 72° North and South latitude for July through October 1978, while GOES-3 coverage was limited to between about 65° North and South latitude. Thus, GOES-3 provided no coverage of the Antarctic ice sheet, and Seasat coverage was limited mainly to the ice sheet margins (Zwally *et al.* 1983*a*). Conversion of range measurements to estimates of ice surface elevation is not a simple task; precision of the altimeter measurements degrades as the slope or roughness of the surface increases, and rapid changes in slope or large surface variations can cause loss of tracking. Over one of the smoothest portions of the Antarctic ice sheet a precision of 0.25 m was obtained (Brenner *et al.* 1983). Accuracy of absolute elevations was estimated to be 2 m or greater over smooth, near-horizontal parts of the ice sheet, and about 15 m over more sloping or rougher ice. Preliminary results for Geosat show errors about 20% smaller than the corresponding values for Seasat (Zwally & Bindschadler 1988). Additional improvements are possible using surface based transponders as point targets to yield measurement accuracies of ± 3 cm (Powell & Johnson 1990). Monitoring vertical displacement of such fixed targets over time could yield very precise estimates of changes in ice sheet elevation.

The Seasat, GOES, and Geosat altimeters were primarily designed to study ocean surfaces. Models of surface conditions typical of the Antarctic ice sheet have been developed that would improve altimeter design for ice sheet applications (Drewry *et al.* 1985). Ice-layer stratigraphy within an ice sheet can also contribute to errors in travel time of the radar pulse, and thus to errors in estimated elevation (Jezek & Alley 1988). Changes in ice structure over time might therefore complicate detection of small changes in the elevations of the polar ice sheets. The next generation of radar altimeters will have significantly improved vertical and horizontal resolution; design specification for the planned Earth Observing System (EOS) radar altimeter is 2 cm for vertical precision, with a footprint of 2 to 10 km over open ocean. Radar altimetry data have also been collected from other platforms, such as from aircraft and constant-density balloons. Although the absolute accuracy (plus or minus 40–60 m for balloon altimetry, plus or minus 30 m for aircraft) is less than satellite altimetry due to positioning errors, a finer spatial coverage is possible using such platforms.

A footprint of between 100 m and 1 km, achievable using laser altimeters, is needed for detailed topographic mapping (Robin 1984). The accuracy of radar altimetry is primarily limited by beamwidth; the narrow beamwidth achievable using laser altimeters removes the problem of variations of surface slope within the beam footprint. The required beamwidth for detailed mapping is achievable using current designs, and greater accuracies are planned for the EOS altimeters in the late 1990s. Such accuracy would be sufficient to detect small (0.03 m a^{-1}) changes in the central Antarctic (Robin *et al.* 1983). Laser altimetry is limited to cloud-free conditions, but frequent satellite overpasses in the polar regions would be likely to yield enough clear sky observations for icesheet monitoring. Combining an airborne lidar (operated as a profilometer) with Global Positioning System (GPS) receivers on board the aircraft and at a fixed ground location appears to be a promising method of achieving repeated measurements over the same transect with a very high vertical accuracy (Krabill *et al.* 1990). As noted earlier regarding radar altimeters, combining the locational precision of the GPS with the vertical precision of the lidar opens the door for very accurate surveys to detect small changes over time.

Although altimetry can provide valuable topographic data, spatial views of ice flow patterns are best observed through the use of high resolution visible band imagery. As a result of the dimensions of typical Antarctic ice streams, features such as drainage patterns, responses to sub-glacial peaks, and changes in ice velocity can be inferred by studying surface patterns (e.g. Swithinbank & Lucchitta 1986). Comparisons of Landsat Multispectral Scanner (MSS) and Thematic Mapper (TM) imagery confirm that the greater spatial and radiometric resolution of TM reveal significantly greater surface detail (Orheim & Lucchitta 1987, 1988). The range of detail visible in an enhanced Landsat image is shown in Fig. 1, which is a portion of a Landsat MSS scene (field-of-view of about 80 m), with the Drygalski Ice Tongue in the lower right, and part of the Prince Albert Mountains in the upper left. The ice tongue extends about 50 km into the Ross Sea.

Landsat imagery has also been used to map ice motion and strain rates by comparing identifiable features from images acquired in different years (Lucchitta & Ferguson 1986, Orheim & Lucchitta 1987). The SCAR nations are actively involved in acquiring a complete set of Landsat TM images which, when compared to MSS data collected about 15 years earlier, should yield precise information on changes in

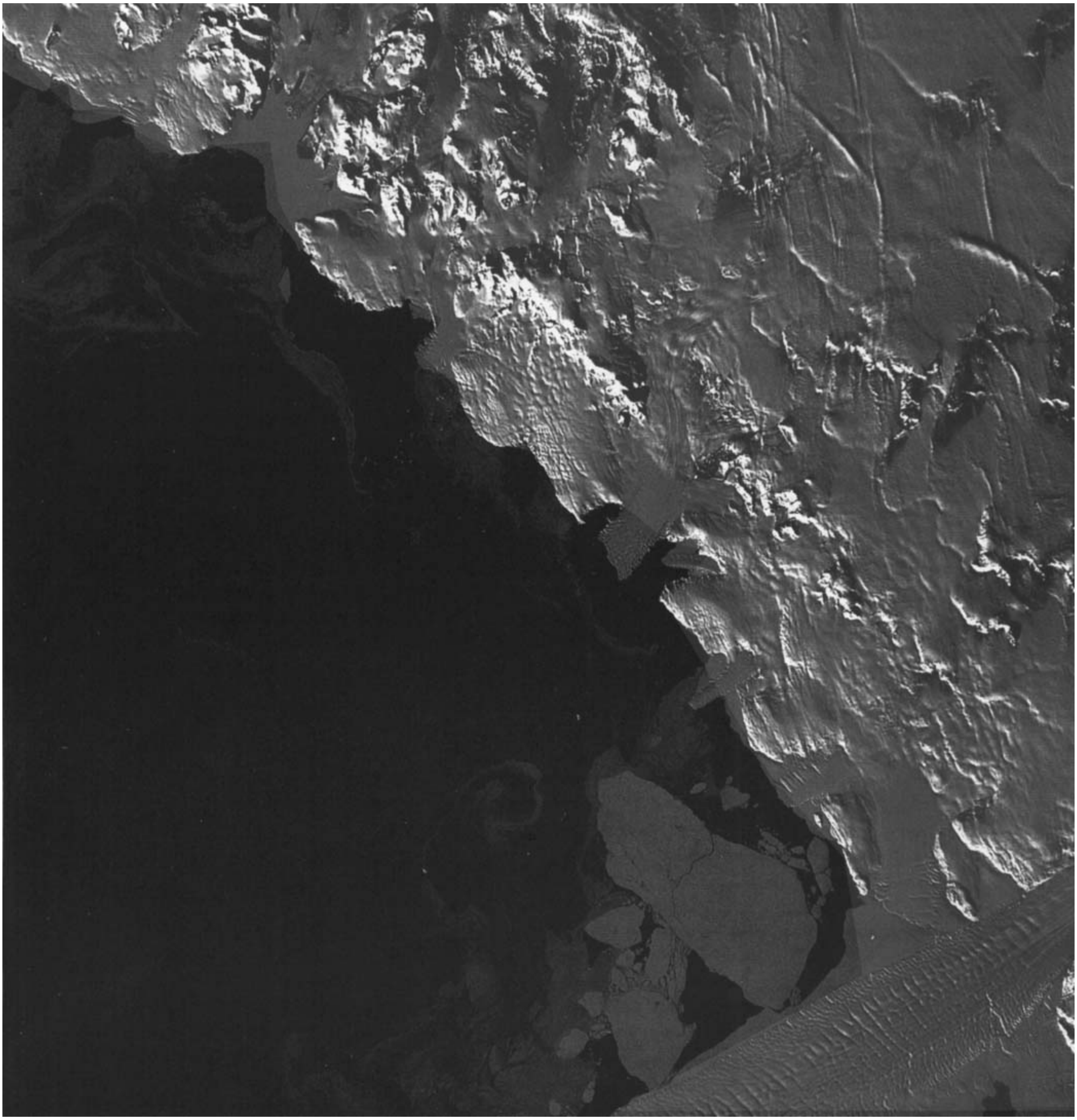

Fig. 1. A portion of a Landsat Multispectral Scanner image (22 February 1973) showing drifting ice eddies, the Drygalski Ice Tongue in the lower right, and part of the Prince Albert Mountains in the top centre. For scale, the ice tongue extends about 50 km into the Ross Sea (image courtesy of B.K. Lucchitta).

surface features over time for the entire Antarctic margin. While relative accuracy of displacements can be high using data such as Landsat and SPOT, absolute geolocation is less precise. Improved satellite tracking and ephemeris will help alleviate these problems. In addition to flow measurements using imagery, the availability of satellite global positioning systems promises to yield useful measurements of absolute position and highly accurate measures of ice motion (Hinze & Seeber 1988).

Mosaics of medium resolution (1–5 km) imagery have been prepared for the entire continent using digital AVHRR imagery (Merson 1989), and DMSP transparencies (Scharfen

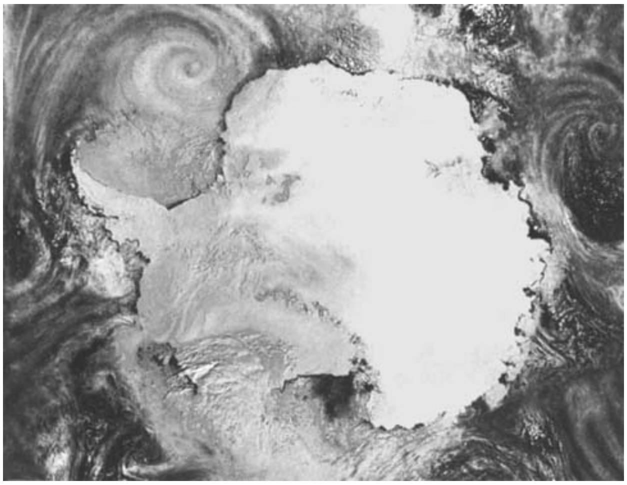

Fig. 2. Mosaic of Antarctica compiled from U.S. Air Force DMSP optical line scan images (2.7 km resolution) collected between 4 and 25 November 1986 and archived at the National Snow and Ice Data Centre (NSIDC).

1987). Fig. 2 shows such a mosaic compiled from DMSP OLS data at a 2.7 km resolution. Although the fine detail needed to map surface flow patterns is lost, these lower-resolution mosaics provide valuable regional views of the ice sheets, as well as sea-ice conditions and weather systems. When used in combination with higher resolution imagery such as Landsat MSS, a time-series of images can show remarkable rates of changes in ice sheet calving (Ferrigno & Gould 1987). Analysis of the 11-year record of AVHRR data could likely reveal changes in the extent of ice shelves. As noted in the following section, AVHRR and DMSP OLS imagery can detect large changes in ice shelf margins, as shown by observations of calving of ice islands. Thomas *et al.* (1983) demonstrate that Seasat radar altimetry could map the Antarctic coastline to an absolute horizontal accuracy of ± 0.1 to 1 km; by combining altimetry (to yield good horizontal positions) with medium resolution satellite imagery (that provides good spatial information but relatively poor horizontal accuracy), a precise monitoring of changes in the ice sheet margins might be possible.

Icebergs, ice islands, offshore operations

Since observations of icebergs are primarily desired to aid shipping and operations, remote sensing techniques applied to iceberg monitoring are well developed for the northern hemisphere. Iceberg production in the Southern Ocean far exceeds that of the Arctic; thus, monitoring of floating ice for operations could become critical if Antarctic shipping or offshore use increases. Some work has been done in support of field operations and, recently, satellite imagery has been used to track the iceberg "B-9", that calved off the Ross Ice Shelf in October 1987 (Rutledge & Scharfen 1988). Intercomparisons of iceberg observations from several remote sensing platforms (e.g., helicopter, fixed-wing aircraft, and satellite) provide useful insights into the advantages of different remote sensing techniques to detect bergs and to track their movement (Keys 1985). When icebergs reach the size of B-9 (roughly about 5000 km^2 as estimated from AVHRR data), tracking is possible using medium resolution imagery. Giant icebergs are visible in both AVHRR and DMSP OLS imagery and the multiple overflights per day of these sensors permit the study of large-scale responses of such bergs to currents and drift interactions with sea ice. Fig.3 shows that considerable detail in the ice shelf, ice margin (including B-9), sea ice, and cloud cover is visible even in degraded resolution (2.7 km versus 0.6 km) DMSP imagery.

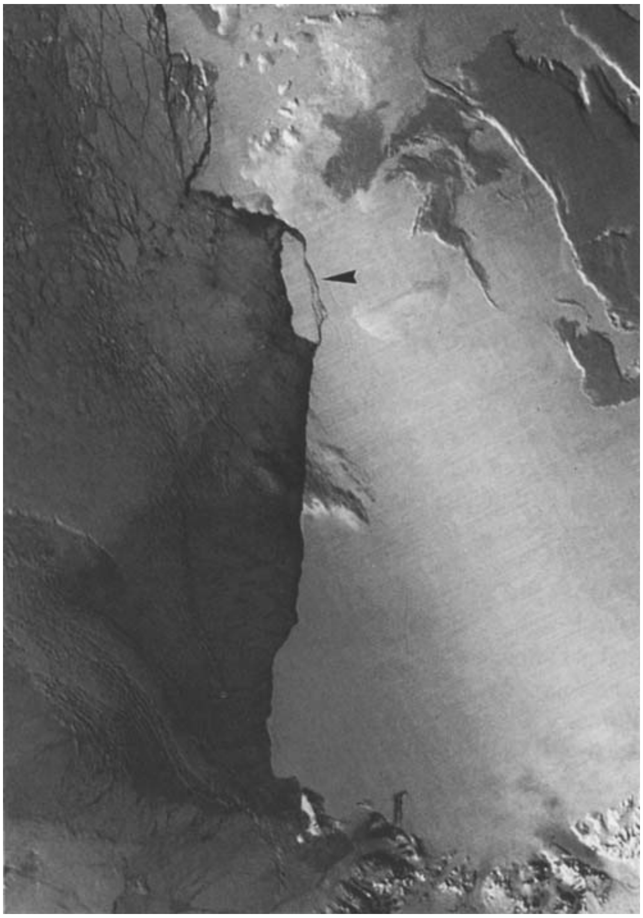

Fig. 3. DMSP optical line scan image (2.7 km resolution) of the Ross Ice Shelf. The ice island B-9 (arrow) is about 170 km along the long axis. Clouds over the ice shelf and different concentrations of sea ice are also visible (NSIDC).

When protection of shipping or offshore operations is of concern, a monitoring program must provide high resolution imagery acquired at rapid intervals. Due to its high resolution and all-weather capability, aircraft-mounted SAR is the mainstay of programs that monitor berg activity in the shipping lanes and drilling locations near the Canadian and Alaskan coasts (Offshore Resources 1985). In addition to detecting bergs, information provided by sequentially-acquired SAR imagery can be used to plot trajectories. By mapping size and displacement, floe kinetic energies can be estimated, and offshore structures can be designed accordingly (Lapp & Ramseier 1983). Since frequent aircraft flights such as those used in the northern oceans are unlikely in the Antarctic, other monitoring methods are needed. Spaceborne imagers, particularly SAR, are good candidates. Spaceborne SAR will broaden the aerial coverage for ice monitoring in Antarctica. However, the detection of icebergs among sea ice at incidence angles typical of a spaceborne SAR is not a straightforward matter, and the data rate of SAR requires that line-of-sight receiving stations be used to minimize the need to record data on board the spacecraft. Japan and the Federal Republic of Germany are planning to establish such stations to receive SAR data collected by the Japanese Earth Resources Satellite (JERS-1) and the European Space Agency (ESA) Earth Resources Satellite (ERS-1). The U.S. hopes to have a station at McMurdo in time to receive Canadian Radarsat imagery.

Icebergs can also be detected and tracked using satellite altimetry if they are beneath the nadir point of the satellite. Rapley (1984) concludes that although altimetry from spacecraft might provide a useful measure of the freeboard of a tabular iceberg (assuming the surface was uniform enough to allow the altimeter to lock onto the surface), the chances of the footprint of the altimeter passing over the iceberg are small. Nevertheless, altimetry might serve as powerful technique of monitoring the iceberg population in Antarctic waters. Thomas (1987) notes that the Seasat altimetry data contain many examples of radar pulse patterns characteristic of those expected from icebergs which need not be directly beneath the satellite to produce a signal in the data record. In fact, McIntyre & Cudlip (1987) describe what they believed to be a giant tabular iceberg visible in Seasat altimeter data, with dimensions comparable to the largest bergs ever recorded in the Antarctic.

Snow cover

Mapping of snow cover is required to assess surface albedo, turbulent heat exchange, accumulation rates on glaciers and ice sheets, and snow extent and volume for runoff calculations. Aerial photographs and high resolution satellite imagery are applicable to each of these areas. Medium resolution satellite data can be used to map snow cover extent, but visible-band imagery provides little information on snow depth or liquid water equivalent. Indirect estimates of accumulation and ablation are possible, such as the use of imagery to map the transient snow line on glaciers. Passive microwave data are used to map snow cover extent, snow depth, and snow water equivalent over land, but are limited by the low resolution of the sensors as well as changes in the snow pack structure that reduce the accuracy of depth and water equivalent estimates (Foster *et al*. 1984). It may be possible to estimate accumulation rates of polar firn using a combination of passive microwave data and an emissivity model, if independently observed surface temperatures are available (Zwally 1977). If several factors such as ice type and ice concentration are known, similar techniques might be used to estimate snow depth or to detect new snowfall over sea ice. Variations in passive microwave brightness temperatures over the ice sheets could conceivably be related to precipitation events, although the errors inherent in estimating the other factors involved in emissivity of the ice sheets or sea ice are likely to mask emissivity changes due to snowfall. Since an indirect estimate of precipitation over large areas can be made based on atmospheric water vapour fluxes (Bromwich 1988), spaceborne soundings of water vapour are valuable for estimating the hydrological budget. Highly accurate laser altimetry such as that described earlier could be used to monitor changes in ice sheet elevation (and if other variables are fixed, accumulation or ablation) to an accuracy of a few centimetres.

Sea ice and ice-ocean-atmosphere interactions

Research and applications of sea ice information require mapping of characteristics such as ice extent, concentration, and ice type on hemispheric scales for climate research as well as on scales of tens of metres for ship operations and to study ice dynamics and detailed ice-ocean-atmosphere interactions. Within this range of spatial scales, we are also concerned with changes in ice condition occurring over days to decades. In addition, useful ice information can be acquired in the visible, thermal, and microwave portions of the energy spectrum. This range of spatial, temporal, and spectral combinations that must be considered means that the topic of ''remote sensing of sea ice'' is too large to treat fully in a general review. Thus, we will limit discussion to selected examples of Antarctic research, as well as some Arctic examples with direct application to Antarctica and the Southern Ocean.

Sea ice extent and concentration

The basic problem in determining ice extent and concentration is discriminating ice from water. In visible and near-infrared wavelengths, the reflectivity of ice ranges from about 0.6 to 0.9 depending on surface condition, while open water is typically less than 0.1. Thin ice reflectivities lie between those of open water and thick or snow covered ice. In both visible and thermal wavelengths, the ability to discriminate ice from open water increases as ice thickness increases. At microwave frequencies, discrimination arises primarily from differences in emissivity (for passive microwave sensing) and surface roughness (radar). Given these spectral properties, virtually any sensor mentioned in this review can be used to study ice extent and concentration. Choices of sensors are governed by limits set by cloud cover and polar winter darkness, as well as by resolution requirements. Because of cloud cover and darkness, most remote sensing research in the Antarctic has focussed on low resolution passive microwave sensors. At the same time, ice mapping for operations has taken advantage of the availability of visible-band imagery from polar-orbiting meteorological satellites like AVHRR, DMSP OLS, and METEOR. Operational ice charts for 1973 to the present prepared by the U.S. Navy and the National Oceanic and Atmospheric Administration (NOAA) at weekly intervals are derived primarily from these data. These ice charts combined with surface observations for pre-satellite years in turn make up the multiyear data sets of ice concentration and extent used for many climate studies. Since these charts are compiled from a variety of image types and surface observations when available, it is difficult to estimate the accuracy of the charts. In general, they have proven to be more accurate for ice edge position than for ice concentration. Care is also required when calculating summary statistics from such data. The choice of averaging method has produced substantial differences in mean annual extremes and monthly variations of Antarctic sea ice derived from the same chart series (Sturman & Anderson 1985).

Visible and thermal-band imagery have been used to map sea ice since the first imaging satellites were launched and applications have been discussed in many publications. Using multi-day hemispheric mosaics of early ESSA imagery to study Antarctic sea ice for three summer seasons, Streten (1983) was able to map ice extent and polynya development, and study ice extent – atmosphere relationships. Although most such studies have focused on Arctic ice, the same data and methods are applicable to the Antarctic. Relatively little work has been done to compare ice concentrations derived from different sensors and field observations. Examples of such comparisons in the Antarctic are given by Streten & Pike (1984) and Comiso & Sullivan (1986).

Airborne and spaceborne radar can provide detailed information on ice cover, with the important advantage of all-weather capability and independence from lighting conditions. Single channel SAR data are most useful for mapping sea ice morphology and ice type, as identifiable by floe shape and roughness. Discrimination of thin ice from open water will probably require a multichannel SAR. Additional information can be gained by studying radar data acquired at different incidence angles. Interpreting this information requires an understanding of the physical and electrical properties of the ice and snow surface, as well as the life cycle of the ice that affects shape and roughness. A number of studies have been carried out combining a suite of remote sensing instruments out to provide such information. Since the ice pack and its snow cover evolve throughout the year, information must be gathered during different seasons; primarily during the transition periods when ice is forming and when melt is occurring (e.g., Livingstone *et al.* 1987). Sea ice data from spaceborne radars have been acquired by Seasat, Soviet Kosmos, and the U.S. space shuttle program (Shuttle Imaging Radar [SIR] A-C). SAR systems will be carried on board ERS-1, JERS-1, and Radarsat during this decade, with a more sophisticated, multichannel SAR planned for the EOS program. Due to the nature of synthetic aperture processing, satellite acquired data may differ little from SAR data collected by aircraft with the exception that the spaceborne SAR image swath can cover a larger area, thus simplifying intercomparisons with other satellite imagery (Carsey 1985). SAR mapping of sea ice in the Weddell Sea using the Shuttle Imaging Radar B (SIR-B) are discussed by Carsey *et al.* (1986) and Martin *et al.* (1987). Based on their work, it appears that SAR techniques developed using Arctic data are directly applicable to the Antarctic sea ice.

Since the launch in 1974 of ESMR on board Nimbus-5, the predominance of studies examining ice concentration and ice extent have been carried out using passive microwave data. In addition to the single channel ESMR, multichannel, dual-polarized passive microwave imagers have flown on three satellites; Seasat (SMMR), Nimbus 7 (SMMR) and DMSP (SSM/I), with a dual channel, single-polarization radiometer on MOS-1. Passive microwave data are similar to SAR imagery in that they are not sensitive to lighting conditions and are relatively unaffected by cloud cover. However, since a passive microwave sensor measures emitted radiation rather than the backscatter from an active source, the energy level available to be sensed is low. As a consequence, passive microwave sensors must collect the emitted energy over a large area to record a measurable signal, or a large antenna must be used. While a field of view for a SAR may be 10 m, the current maximum spatial resolution of SSM/I is about 12.5 km. The advantages of passive microwave data are their greater sensitivity to ice type, ice thickness for thin ice, open water/ice discrimination, extensive spatial coverage, and more frequent observations. A map of SMMR brightness temperatures gridded to a 60 km pixel size is given in Fig. 4. Variations in brightness temperatures are apparent over the ice sheet (associated mainly with surface temperatures), within the ice-pack (due primarily to ice concentration), and over open ocean (due to weather effects). As with SAR, the characteristics of microwave emissions from sea ice have been studied by many investigators. Studies of the passive microwave properties of Antarctic sea ice have been carried out by Comiso & Zwally (1982), Comiso & Sullivan (1986), and Comiso *et al.* (1989). The value of comparing simultaneously acquired passive microwave data and medium resolution imagery to interpret ice conditions is shown by Takeda & Wakabayashi (1989), using MOS-1 data. Atlases of ice concentration for the Southern Ocean have been compiled from ESMR (Zwally *et al.* 1983*b*) and from SMMR data (Comiso & Zwally 1989). Examples of mean monthly ice concentrations from this atlas are shown in Fig. 5. Both publications provide discussions of algorithms to extract ice information from passive microwave

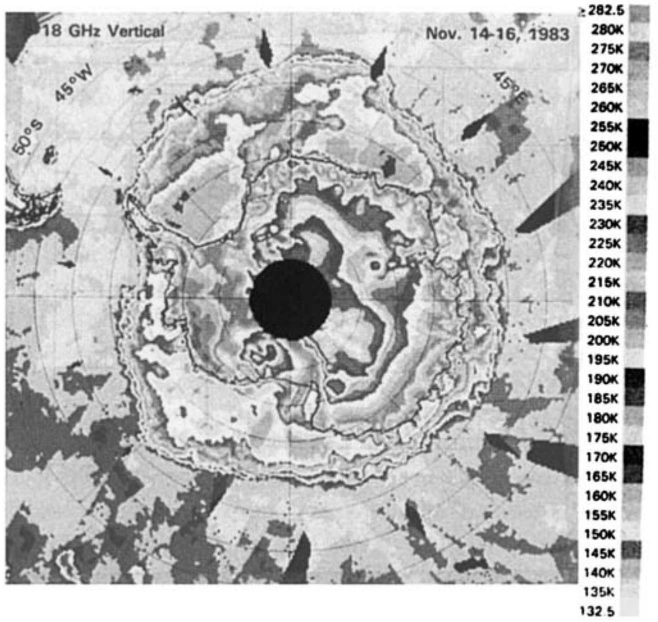

Fig. 4. Map of SMMR brightness temperatures in Kelvins (2-day average; 18 GHz, vertical polarization) for Nov. 14-16, 1983. Values range from about 160 K over the highest portions of central Antarctica, to about 235 K over most of the sea-ice cover (from Comiso & Zwally 1989).

data and describe special considerations for passive microwave ice mapping in the Southern Ocean. In general, ice concentration accuracies appear to be about ± 5% during midwinter. Accuracy tends to be highest in consolidated ice packs consisting of a single ice type (i.e., thick first-year ice). Passive microwave algorithms, sea ice emissivity characteristics, and sources of error are discussed by Zwally *et al.* (1983*b*), Gloersen & Cavalieri (1986), Comiso & Sullivan (1986), and Comiso *et al.* (1989).

Although the spatial resolution of passive microwave data is low relative to many other sensors, this scale of observations can be an advantage for climatological studies and is well suited to sea ice and climate models. Data acquired daily covering an entire hemisphere can be studied with relative ease. Multi-year records of such images can be analyzed to detect trends in ice extent and ice covered area, and to study spatial and temporal changes in ice patterns, although factors such as degrading sensor performance or changes in non-sea ice factors such as wind speeds or cloud cover must be carefully considered in searching for small changes over time and space. The ESMR time-series for the Antarctic is discussed in detail by Zwally *et al.* (1983*b*). Interannual changes in Antarctic sea ice have been studied by Rayner & Howarth (1979) using ESMR data. A combination of the ESMR and SMMR records for both hemispheres is described by Gloersen & Campbell (1988). Cavalieri (1989) reviews these and other recent remote sensing studies of polar ice variability.

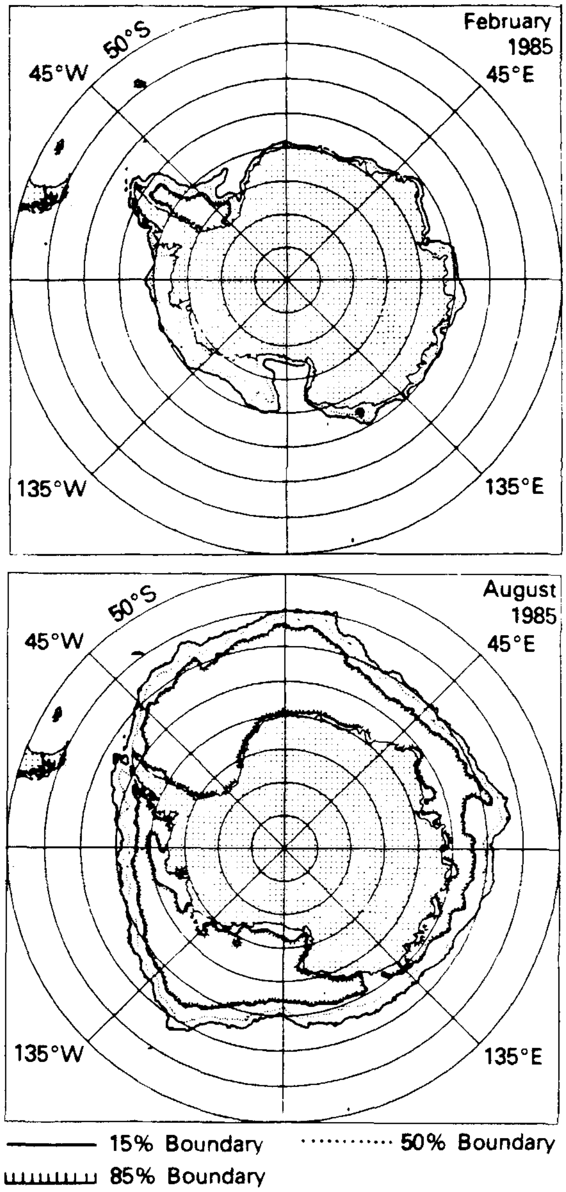

Fig. 5. Monthly averages of SMMR-derived sea-ice concentrations for February and August 1985 (from Comiso & Zwally 1989).

Although visible and thermal-band imagery at both high and medium resolution can be used to study ice motion and dynamics, the need for sequential images uncontaminated by cloud cover point to SAR as the best instrument for such studies. Given the potential of SAR, a number of ice motion studies have been performed for the Arctic, and automated methods to track ice motion are being developed (e.g., Fily & Rothrock 1986; Kwok *et al.* 1990). Passive microwave data have demonstrated some ability to track homogeneous regions of brightness temperature and perhaps ice type on much larger scales (Gloersen *et al.* 1978). Remotely sensed sea ice data are also used to validate computer models by comparing modelled versus observed ice extent, concentration, and ice dynamics (e.g., Hibler & Ackley 1983). Spaceborne SAR imagery are particularly well suited to detailed studies of modelled versus observed ice dynamics. Passive microwave-derived ice concentrations have not yet been input directly into large-scale models; only recently have climate models been run with even rudimentary treatments of the open water fraction within the ice pack (Ledley 1988, Simmonds & Budd 1989). Methods of assimilating remotely sensed data into models is an active area of research.

Ice-ocean-atmosphere interactions

In the southern hemisphere, the area with sea ice changes from about 4 x 10^6 km^2 in February to about 20 x 10^6 km^2 in August and September. Given the insulating properties of ice, effects of ice growth, and large difference in albedo between ice and water, this changeable sea ice cover can affect the oceans and atmosphere in a variety of ways (Parkinson *et al.* 1987). Thus, investigations of sea ice variability and ice-ocean-atmosphere interactions have been the topics of a number of studies. The discussion here will be limited primarily to Antarctic investigations.

Ice-ocean-atmosphere studies that have used remote sensing have focussed primarily on relationships between ice extent and concentration and large-scale to synoptic-scale pressure patterns in the Southern Ocean, or on polynya development and the contribution of new ice growth to deep water formation (Streten & Pike 1980, Streten 1983). Ackley (1980) and Budd (1986) review some of the ice-ocean-atmosphere interactions in the Southern Ocean. The availability of passive microwave data has led to a number of studies of these interactions. Apparent associations between the ice edge and the location of the circumpolar trough and cyclogenesis have been noted using passive microwave data and meteorological information (Parkinson & Cavalieri 1982, Carleton 1981*a*, 1981*b*, Howarth 1983). Comparison of Antarctic ice extent shown in Navy/NOAA ice charts with mean monthly meteorological data suggests that oceanic heat flux might account for as much as 50% of the ice melt during summer (Gordon 1981). Since present long-term satellite-derived sea ice climatologies may overestimate the amount of ice cover (Streten & Pike 1984), such potential errors must be included in energy and mass budget calculations.

The need for a long record of satellite-derived ice extent and concentration in order to search for climatic trends is revealed by the short-lived fluctuations that have been noted in the existing data sets. Examinations of different lengths of records have yielded different interpretations of trends in Antarctic sea ice extent and ice-covered area (Chiu 1983*a*, 1983*b*), and in statistical interpretations of large-scale linkages between ice extent and atmospheric circulation (Chiu 1983*b*, Carleton 1989). Additional information on short-period, synoptic-scale interactions that may not be captured in meteorological analyses can be gleaned by combining passive microwave data and outgoing longwave radiation as measured from space (Cahalan & Chiu 1986). Passive microwave data have proven particularly useful for studying spatial variability in the ice pack, and relating these variations to large-scale oceanic and atmospheric forcings. The mean decrease in Antarctic ice extent observed during the mid-1970s has been attributed to the development of the Weddell Polynya (Zwally *et al.* 1983*b*, Carsey 1980). As noted earlier, modelling of the formation and development of such features are aided by the availability of satellite observations to validate model performance. Comparisons of modelled and satellite-derived ice extents for the Weddell Sea and Weddell Polynya are presented by Hibler & Ackley (1982) and Parkinson (1983).

Remote sensing analyses of sea ice extent and concentration in the Antarctic have also examined the interactions between winds, ocean, and the development of polynyas and leads within the ice pack, and the associated brine production and haline convection. Topics of study include the forcing mechanisms controlling the open water areas, and the effects of these open water areas on heat flux, ice growth, and brine production (Sturman & Anderson, 1986, Zwally & Gordon 1985, Bromwich & Kurtz 1984). On more local scales, backscattered energy from downward-looking lasers can be used to detect leads in the sea ice, and to discriminate open from refrozen leads. The scale of passive microwave data is well suited for time-series analyses of polynya formation (Comiso & Gordon 1987, Cavalieri & Martin 1985, Jacobs & Comiso 1989). While some wind flow patterns have been inferred from thermal imagery (Parish & Bromwich 1989), the study of interactions of katabatic winds and sea ice concentration are likely to rely on a combination of remotely sensed ice data and modelled or station-observed winds.

Ocean and lower atmosphere

Ocean and atmosphere variables observable from remote sensing platforms include sea surface height, sea surface temperature, ocean colour, waves, surface wind speed or surface stress, cloud cover, cloud liquid water, atmospheric water vapour, atmospheric temperatures, precipitation rates, haze and aerosols. Although not written specifically with polar applications in mind, several useful texts and reviews of remote sensing applications in oceanography, meteorology, and climatology are available (e.g., Robinson 1985, Vaughan 1987, Susskind *et al.* 1984, Chahine 1982, Henderson-Sellers 1984). Sounders are required to provide atmospheric temperature and water vapour profiles, while passive microwave imagers can be used to estimated integrated columnar values for water vapour and cloud liquid water. Satellite sounder data (Olesen 1987) have the advantage of much greater horizontal sampling than can be achieved using radiosondes. Drawbacks for polar applications include low-level temperature inversions, scarcity of radiosonde observations for calibrating sounder data, and errors in determining cloud cover due to the high altitude and low temperatures of the Antarctic ice sheet (Lutz & Smith 1986). Improvements in processing using existing sensors (Lutz & Smith 1988), as well as data from new sensors, will expand the use of sounder data for polar applications, although observations from upward-looking sounders are likely to still be required for detailed boundary layer observations (Culf 1989). For some uses, the low spatial resolution of existing sounders yields data directly comparable to and compatible with low resolution imagery. Combinations of sounder and imager data could be especially useful for applications that require concurrent information on surface and atmospheric conditions. In addition to sounders, earth radiation budget (ERB) data (House 1985) also have a variety of applications for large-scale energy balance studies (Taylor & Stowe 1984, Charalambides *et al.* 1985) including, as noted earlier, for ice-ocean-atmosphere studies. Laser remote sensing provides information on atmospheric chemical composition and pollutants (Killinger & Menyuk 1987)

The potential roles of remote sensing for polar oceanography generally involve the straightforward application of mid-latitude techniques to the Southern Ocean (Gordon 1983, Mognard *et al.* 1983), although the presence of sea ice and the ice sheets complicates the use of some data types. For example, sea surface temperature and wind speeds cannot be reliably mapped within the ice pack due to the modification of temperatures and emissivities by ice within the sensor's field-of-view. Both surface temperature and wind speed can be estimated using passive microwave radiometers. Mapping of wind speed and direction can be carried out using radar scatterometers, such as that carried on board Seasat and planned for the Navy Remote Ocean Sensing System (N-ROSS) satellite that has been considered for launch in the early 1990s, and JERS-1, as well as scatterometers scheduled to be included on the EOS platforms. Surface temperature and wind speed estimates might be achieved by filtering out the effects of sea ice in, for example, a passive microwave footprint. Combinations of the different sensors on the EOS platform will probably be useful in this regard. When cloud patterns can be reliably detected, wind fields can be inferred by tracking cloud motion in sequential images. Over open water, the accuracies of surface temperature, wind speed, and integrated columnar water vapour measured using Seasat SMMR data are approximately 1.2°C, 2.5 m s^{-1}, and 0.4 g cm^{-2}, respectively (Njoku & Swanson 1983). Sea surface temperatures (SST) are useful for studying ocean fronts, circulation patterns and mesoscale eddies. Thermal imagery from high and medium resolution sensors provide information on features such as the Antarctic Polar Front, and ice-edge temperatures in the Ross and Weddell seas (Legeckis 1976, 1978). A variety of applications for satellite-derived SST and wind speeds exist in the Southern Ocean. Such studies could be expanded to examine in greater detail conditions near the sea ice edge by combining SST and wind speeds with satellite-derived ice concentrations. For larger scale SST distributions, passive microwave data may be appropriate (Njoku 1985). The international Tropical Ocean Global Atmosphere (TOGA) program has listed desired accuracies of 0.3°K for SST and 0.5 m s^{-1} for surface wind speed; new instruments designed to achieve these accuracies are planned for the earth resources satellites and EOS. In mid and high latitudes where atmospheric water content is lowest, AVHRR can achieve SST accuracies of about 0.7°K. When combined with NOAA sounder data for atmospheric corrections, accuracies of about 0.2°C to 0.3°C are possible (Schlussel *et al.* 1987). In addition to atmospheric effects, factors such as variations in emissivity with viewing angle, changes in surface roughness, and sensor calibration act to limit accuracy (Rossow *et al.* 1989). Sensors planned for ERS-1 and EOS will have the capability to view the same surface from two angles, which should significantly improve atmospheric corrections. A problem with all existing and planned remote sensing of SST is that the measured temperatures reflect only the temperatures at the very surface of the ocean, rather than the temperatures measured by buoy and ship observations against which satellite measurements are compared, and which may be more meaningful for the study of oceanic processes.

Cloud cover (cloud fraction and cloud optical depth) is recognized as perhaps the greatest unknown in climate investigations, particularly at high latitudes. Remote sensing of cloud cover over the Southern Ocean and Antarctica is complicated by polar darkness, persistent cloud cover, a rapidly changing surface (sea ice), and the presence of a cold ice sheet high albedo. All of these factors tends to confuse automated cloud-mapping routines (Rossow *et al.* 1985, Raschke *et al.* 1989), and warrant the development of polar-specific mapping algorithms (Key & Barry 1989, Ebert, 1989). Useful information on cloud cover can also be gathered using manually interpreted cloud patterns (e.g., Carleton 1987) and sounder data. A particularly valuable approach, which yields a variety of atmospheric variables in addition to cloud cover, uses a combination of HIRS and MSU data collected by the Tiros-N Operational Vertical Sounder (TOVS) (Susskind *et al.* 1987, Claud *et al.* 1989). For clear sky pixels, surface reflectances and surface temperatures can be estimated (Rossow *et al.* 1989).

Ocean biota

One of the principal applications of remote sensing in the polar regions for biological studies has been the use of ocean colour sensors to map biological activity in shelf waters and at the sea ice margin. The Coastal Zone Colour Scanner (CZCS) on board Nimbus 7 provided the impetus for much of this work (e.g., Sturm 1983, Maynard & Clark 1987). High resolution sensors, such as Landsat, have also been used for localized studies, and should be particularly useful for detailed investigations along the sea ice margin. Combinations of CZCS and SMMR data are especially useful for studying productivity near the marginal ice zones

(Sullivan *et al.* 1988). AVHRR reflective channels have shown some capability for monitoring phytoplankton concentrations, especially when concentrations exceed 1.5 mg m^{-3} (Gallegos *et al.* 1989). Imaging spectrometers planned for EOS will be valuable for studying slight fluctuations in water colour, and might permit precise estimates of productivity if spectral measurements can be calibrated to distinguish chlorophyll levels from sediments or pollutants. The high and medium resolution imagers on board MOS-1, as well as the sensors planned for ERS-1 and JERS-1, also offer some potential for studying ocean colour and productivity. In addition to ocean colour viewing in visible wavelengths, thermal channels on a variety of sensors can be used to define different water masses, current interactions, and zones of upwelling. As is the case with ocean colour experiments, many studies have examined local and regional distributions of sea surface temperature from high and medium resolution sensors as noted in the previous section (Klemas 1980, Rimmer *et al.*, 1987). Similar techniques are suitable for investigations in the marginal ice zone. New satellites that are planned for launch in this decade and are capable of mapping ocean colour include SeaWIFS (Wide-Field Sensor), which may be carried on board a Landsat platform in the early 1990s, and several of the instruments scheduled for the EOS program.

Environmental protection

For all research and development activities in Antarctica environmental protection must be a key concern. Baseline studies need to be carried out to map existing conditions, and should be followed up by a consistent monitoring program. Remote sensing techniques might be used to locate the least-sensitive sites for construction, or to define regions or conditions of particular hazard to shipping. Since some environmental impact is inevitable, remote sensing can play a role in assessing environmental damage, attributing blame, and aiding mitigation efforts. The application of remote sensing techniques for environmental monitoring and protection is common in many nations. As environmental impacts in Antarctica become more critical, or at least more publicized, it is likely these techniques will be applied there as well. The U.S. National Science Foundation recently conducted a workshop to discuss long-term environmental monitoring in the Antarctic. The workshop emphasized that "parameters of specific ecosystems must be identified and the current state of each ecosystem evaluated," and that remote sensing and geographic information systems could contribute to this effort (National Science Foundation 1989*b*). Drafts of the Antarctic Minerals Convention preclude "minerals activities that will have significant effects on or cause significant changes..." in a variety of factors ranging from species populations to world climate and weather patterns (Kimball 1988). Given such concerns, environmental impact assessments for Antarctic activities may become commonplace. The New Zealand Antarctic Programme has reviewed some of the appropriate criteria for such assessments (Keys 1988, Broady 1988), noting in particular the need to establish baseline conditions in unique areas, and the need to monitor these areas for environmental impacts. Such requirements are similar to those for environmental impact statements (EIS) in the U.S., where remote sensing has proven valuable for EIS development. Studies in the northern hemisphere can be extrapolated to demonstrate potentially useful techniques for Antarctica (Dey & Richards 1981). High resolution data from aircraft may be used to monitor animal populations, to track human activities, or to identify trespassers or sources of contamination. However, before assuming that remote sensing can make a significant contribution to environmental monitoring in Antarctica, the variety of problems that affect remote sensing in high latitudes must be considered, and potential impacts of remote sensing activities themselves, such as aircraft overflights and construction of receiving stations, must be addressed.

For environmental monitoring, geographic information systems (GIS) that incorporate a variety of data types and aid in the analyses of combinations of these data will probably prove valuable, as they have for other similar applications. Environmental monitoring will require the assembly of a variety of maps depicting protected zones, habitat sites, zones of national responsibility, and others. Such maps usually exist as line drawings or as digital X,Y coordinates ("vector" form) as opposed to remotely sensed imagery, digital terrain data, meteorological fields, and other data that are typically stored in grid (or "raster") form. Modern GIS systems handle both data types, and permit the overlay and combinations of vector maps and raster imagery. Thus, it is a simple matter to compare an aircraft acquired image showing human activity with maps of claim boundaries or protected zones to determine whether the activity is complying with regulations.

Other applications

In order to treat some aspects of remote sensing in the Antarctic in sufficient detail, other important remote sensing applications have been not been discussed. For example, remote sensing of the upper atmosphere and atmospheric trace gases for ozone depletion studies and greenhouse gases, among others, warrant reviews of their own (Pyle 1987, Jones *et al.* 1986, Jackman *et al.* 1986). Studies of reductions in total ozone in the Antarctic summer compared to winter values, and linkages to circulation of the upper atmosphere, are excellent examples of combinations of satellite observations (e.g., Nimbus 7 TOMS) and *in situ* measurements such as instrumented balloons. Continued flights of spaceborne spectrometers, such as the SBUV instruments, combined with new sensors, such as the Upper Atmosphere Research Satellite (UARS) scheduled for launch in the early to mid 1990s, and the Mesosphere-Thermosphere Explorer Mission (MTEM) in later years will aid in studies of the coupled chemistry and dynamics of the stratosphere and mesosphere.

Minerals exploration using remote sensing typically relies on structural mapping, detection of spectral characteristics of minerals, or secondary indicators such as chemical uptake by vegetation. Such indicators are rare in Antarctica, although Landsat imagery has been used to map structural features and spectral signatures in dry valleys (Lucchitta *et al.* 1987). An interesting unique application of remote sensing is the search for meteorites on the Antarctic ice sheet. While the meteorites themselves cannot be detected, the blue-ice zones within which meteorites are concentrated can be seen in Landsat imagery (Lucchitta *et al.* 1987, Graham & Annexstad 1989). Such areas of blue ice also have some potential as aircraft landing sites. As spectral and spatial resolution of sensors improve in the future, such specialized applications of remote sensing are likely to become more common.

Next generation remote sensing: new sensors and the earth observing system.

In the 1970s and 1980s, remote sensing in the polar regions using spaceborne instruments has been carried out using data from a combination of operational sensors (e.g., AVHRR, DMSP, and Landsat), and research platforms (Nimbus 5 and Nimbus 7) that have typically provided useful data long past their scheduled lifetimes. These instruments have demonstrated the usefulness of continued observations using a relatively uniform set of sensors, as well as the value of sensors tailored for specific applications.

The Earth Observing System (EOS) (National Aeronautics and Space Administration 1989), a cooperative effort between the United States, the European Space Agency, and other nations including Japan, is designed to continue this approach by providing data streams of demonstrated value combined with new instruments to study features in greater spectral and spatial detail. New sensors to be launched by ESA and the Japanese, as well as new SPOT and Landsat platforms, the SSM/T temperature sounder on DMSP, and the addition of a 1.6 micrometer channel on AVHRR for cloud discrimination, follow a similar path. Single-channel synthetic aperture radars are to be carried on board Radarsat (Canada), E-ERS 1 (ESA), and J-ERS 1 (Japan). The Japanese MOS-1 is a scaled-down precursor to EOS, with a Landsat-type sensor, an AVHRR-type sensor, and a passive microwave radiometer all on the same platform. The ERS satellites will carry improved imaging radiometers and are scheduled to include a wind/wave scatterometer. These new platforms and others such as Sea-WIFS, NROSS, and UARS will offer improved sounders, imagers, and greater radar altimetry coverage, possibly followed in the late 1990s by the first EOS polar-orbiting platform.

The particular research themes EOS is designed to assist include the global radiation budget, the structure, composition, and dynamics of the atmosphere and land surface, the earth's biogeochemical cycle, characteristics of precipitation and the cryosphere, and the dynamic motion of the planet. Such all-encompassing themes require the assimilation of a variety of data types. EOS is designed to greatly aid such assimilation over past and current practice by acquiring multiple data types from a single platform (thus minimizing problems of spatial and temporal location) and archiving data in locations and forms accessible to researchers from many fields. Given the multidisciplinary nature of most aspects of polar research and the reliance on remote sensing techniques, the EOS program could be particularly beneficial to Antarctic studies. For Antarctic applications, researchers can expect to be able to combine more detailed observations of surface characteristics (sea ice, SST, ocean colour, topography, surface roughness, etc.) with a wider array of atmospheric observations. In light of this potential, the planned EOS instruments are briefly considered below.

Some of the instruments planned for EOS program (based on the May 1989 EOS Handbook [National Aeronautics and Space Administration 1989]) are:

Moderate Resolution Imaging Spectrometer-T and N (MODIS-T and MODIS-N),
Atmosphere Infrared Sounder (AIRS),
High Resolution Imaging Spectrometer (HIRIS),
Synthetic Aperture Radar (SAR),
Geoscience Laser Ranging System (GLRS),
Laser Atmospheric Wind Sounder (LAWS),
Intermediate Thermal Infrared Radiometer (ITIR),
Advanced Microwave Scanning Radiometer (AMSR),
Medium Resolution Imaging Spectrometer (MERIS),
Atmospheric Lidar (ATLID),
Advanced Microwave Sounding Unit A and B (AMSU-A, AMSU-B),
Radar Altimeter (ALT),
High Resolution Research Limb Sounder (HIRRLS),
High Resolution Imaging Spectrometer (HRIS),
High Resolution Microwave Spectrometer Sounder (HIMSS).

While previous instruments had fixed configurations (pointing angles, number and types of channels, etc.), EOS instruments are generally characterized by built-in flexibility that allows ground controllers to select subsets of channels and pointing angles. Each of the EOS sensors is either a significant upgrade of an existing sensor, or an essentially new instrument. For example, MODIS is a much improved type of AVHRR that includes a tilting and non-tilting version, up to 64 spectral channels, and a maximum spatial resolution of 214 m. HIRIS is roughly comparable to Landsat and SPOT, but is pointable both along-track and across-track, and offers higher spatial resolution and nearly 200 spectral bands. The SAR will probably be mounted on a separate free-flying platform and is to be a three frequency instrument with multiple combinations of transmit and receive polarizations, variable incidence angles, swath width, and pixel sizes. HIMSS is a passive microwave instrument similar to SSM/I, but with more channels and higher spatial resolution (5 km to 50 km). HIRRLS will observe temperatures and chemical constituents in the upper atmosphere at a spatial and spectral resolution considerably greater than that currently available. New instruments include the lidars and LAWS, which will provide cloud top heights and precise surface elevations and wind speeds. Although the instrument list planned for EOS may continue to evolve, versions of the sensors listed above are likely to form the core of the EOS experiment. The earliest likely launch of an EOS polar-orbiting platform is currently listed as December 1996. Platforms supplied by ESA and Japan would be launched at a later date.

As the above list of planned instruments indicates, we can expect better spectral resolution over the solar, infrared, and microwave portions of the spectrum, much improved spatial resolution (particularly in the "medium resolution" wide-swath sensors such as MODIS), higher vertical and spatial resolution and accuracy in sounders and altimeters, and a general improvement in calibration and sensor stability. For Antarctic research, these advances will combine to particularly benefit studies of cloud properties, sea ice mapping, and atmospheric profiles of state variables. The fine spectral and spatial resolution achieved by the planned imaging spectrometers may permit the detection of subtle changes in surface conditions arising from human activity, and will probably serve as valuable comparative data for the interpretation of different sea ice types, sea ice surface conditions, ocean colour, and flow patterns and surface conditions on the ice sheets. As demonstrated by the SPOT instrument and recent work using AVHRR data, imagery from different pointing angles can be used to construct three-dimensional views useful for terrain mapping; similar composites will be possible using the steerable EOS sensors. In summary, the remote sensing instruments planned for the 1990s will: 1) improve existing applications and permit new studies, 2) continue adding to the extension of existing remote sensing records to aid time-series analyses, and 3) provide new data types particularly useful for earth systems studies of interactions between ocean, atmosphere, and the cryosphere.

Just as combining multiple spectral channels became common with the launch of multispectral imagers in the 1970s, combinations of data from several sensors will probably become a common solution to study complex physical processes and systems. One challenge of remote sensing will be to develop new data classification and data exploration schemes (using, for example, artificial intelligence methods) to convert raw data into information. An expanding role for such information will be in the validation and operation of climate and process models. In a practical sense, the derivation of geophysical parameters from remotely sensed data, with appropriate accuracy estimates and validation, must be combined with mechanisms to archive and retrieve data in order to take full advantage of the anticipated growth in information. One of the most significant areas for advancement in remote sensing applications is not related to new and better sensors, but rather to the ability of researchers to find and work with existing data. In the past, remotely sensed data were often acquired for a specific project or task; once used, transfer of data to other researchers or storage for future studies was typically not of major concern, or could not be supported using research funds. In recent years, organizations have been formed in or supported by government agencies with the mission of cataloguing and protecting satellite data. The National Aeronautics and Space Administration (NASA) Master Directory, for example, can be used to find the archive locations for many types of imagery and other information. A partial list of archiving centres or information sources for Antarctic remote sensing and related data is given in Appendix 1. The volume and variety of data to flow from the EOS program, combined with the expected demand for data to study a range of problems, will increase archiving requirements by orders of magnitude. Unlike previous programs where data archival was an afterthought, planning for data storage and distribution through the EOS Data and Information System (EOSDIS) is already underway.

Conclusion

As the examples presented in this review show, remote sensing is used in a variety of applications in Antarctica and the Southern Ocean, with the potential for considerable sharing of data and techniques among different disciplines. Remote sensing is particularly valuable in the polar regions. In the case of Antarctica, its contribution to mapping the continent and ice sheet, to delineating the seasonal sea ice cycle and the existence of the Weddell Polynya, to tracking icebergs, and to monitoring the Antarctic ozone hole is clearly substantial. Remotely sensed imagery and sounder profiles will be increasingly important for the study of climate change, and for integrated analyses of the atmosphere, hydrosphere and biosphere envisioned under the umbrella of earth systems science. However, applications in high latitudes must overcome inherent difficulties that make some variables, such as cloud properties, particularly difficult to map. New sensors should help to overcome some of these limitations, and continued launch of operational instruments will improve our ability to detect significant climate signals in remotely sensed data. Researchers interested in acquiring data now have several archiving centres and computerized directories to turn to for assistance. Given the possibility that instruments, observations, and techniques will significantly improve and expand in the 1990s, this review may provide a starting point for those interested in applying remote sensing to research in Antarctica.

Acknowledgments

This work was funded in part by the NOAA Climate and Global Change Program and through NOAA Cooperative Agreement NA85RAH05066.

APPENDIX 1: Partial List of Data Centres and Information Sources

The NASA Master Directory:

Computer directory of space and earth sciences data sets. Contains descriptions of data sets and describes methods for searching for data based on user-specified parameters. Provides links to other catalogues and data centres.

Contact: (301) 286-9790 for more information.

NASA Space Sciences Data Centre:

Central facility for NASA data sets, and link to oceans, climate, land, and planetary data systems.

Contact: NSSDC, Code 633.4, Goddard Space Flight Centre, Greenbelt, MD USA 20771. (301) 286-4136.

World Climate Data and Information Referral Service (INFOCLIMA):

Master directory to world-wide climate and related data archives.

Contact: The World Climate Data Program, World Meteorological Organization, C.P. 2300, CH-1211 Geneva 2, Switzerland

Earthnet User Services:

European Space Agency catalogue of earth observation information received at European ground stations.

Contact: Earthnet User Services, ESRIN, via Galileo Galilei, 00044 Frascati, Italy. (06) 94180360

National Snow and Ice Data Centre, World Data Centre-A for Glaciology (Snow and Ice):

Digital and non-digital data sets pertaining to the cryosphere (e.g., Antarctic Climate Data; Glaciological Report GD-15, Antarctic Meteorological Workshop; GD-20).

Contact: NSIDC, CIRES, Campus Box 449, University of Colorado, Boulder, CO,USA. 90309. (303) 492-5171.

National Oceanographic Data Centre:

Contact: NODC, 1825 Connecticut Avenue, NW, Washington, D.C. USA 20235. (202) 673-5549.

Earth Observations Data Centre:

ERS-1 products and development.

Contact: EODC Project Office, R16 Building, Royal Aerospace Establishment, Farnborough, Hampshire, GU14 6TD, UK. 0252-24461

Alaska SAR Facility:

An archive centre for ERS-1 synthetic aperture radar data.

Contact: ASF, Geophysical Inst., University of Alaska, Fairbanks, AK, USA 99775-0800. (907) 474-7371.

National Climate Data Centre:

Historical weather information (surface observations, satellite data, etc.)

Contact: NOAA NESDIS, Federal Building, Asheville, NC, USA 28801. (704) 259-0682.

Satellite Data Services Division:

Variety of satellite acquired products.

Contact: NOAA/NESDIS/NCDC, Satellite Data Services Division, World Weather Building, Room 100, Washington, D.C. USA 20233. (301) 763-8111.

Scripps Institute Antarctic Research Centre:

NOAA AVHRR digital imagery received at McMurdo.

Contact: Antarctic Research Centre, Mail Code A-014, Scripps Institution of Oceanography, La Jolla, CA USA 92093. (619) 534-3785.

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