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THE APPLICATION OF MICROWAVE REMOTE SENSING FOR SNOW AND ICE RESEARCH

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THE OBSERVATIONAL BARRIER

That part of the Earth's surface least known and understood is the cryosphere, which we take to include sea ice, ice sheets, snow, glaciers, and permafrost. After several millenia of exploration and discovery by civilized man, the North and South Poles were reached for the first time only in this century. Few chapters in the history of exploration resound with names such as those associated with the Arctic and Antarctic--names connoting courage and daring coupled with keen intelligence and observational abilities--men such as Nansen, Shackleton, Sverdrup, Amundsen, Scott, Rasmussen, and Peary, all of whom performed their great tasks within the last century. The largest single coordinated effort by mankind to increase our knowledge of polar geophysics, the International Geophysical Year (IGY) occurred only 2 decades ago. Hence, a vast part of our knowledge of ice and snow is recently acquired.

The reason why our knowledge of polar snow and ice processes is so recent and relatively limited can be simply stated: the Arctic and Antarctic are extraordinarily difficult and expensive environments in which to carry out surface investigations. This is the basis of the "observational barrier" surrounding the polar regions. Since the IGY, it has become increasingly clear that many ice processes occur over large space scales and at short time scales. Consequently, synoptic data are necessary to study the dynamic interactions of ice with the ocean and atmosphere systems. Thus, when the meteorological satellite program was started at the end of IGY, there was considerable optimism that "cause and effect" studies of many ice processes could finally be attempted with the new information.

But the observational barrier was not to be so easily broken. The early coarse resolution TIROS imagery, and later finer resolution Nimbus, NOAA, and Landsat imagery were useful but limited. They delineated sea-ice extent and morphology for restricted space and time scales, mapping only parts of Antarctica and Greenland, and poorly distinguishing snow from cloud cover. It was apparent that the synoptic scale data needed to study the most important ice and snow processes could not be acquired by satellites that carried only sensors for visible wavelengths. Polar regions are virtually dark for half the year and frequently cloudy when not. Indeed, the areas which are most dynamic are also the most cloudy, such as the boundaries of the sea-ice packs. Furthermore, sensing ice with visible and infrared wavelengths gives limited information about the state of the viewed surface and nothing about what is beneath it. There is no penetration of the medium to probe the internal structure and physical characteristics of the snow and ice.

A little more than a decade ago, polar scientists from several nations began to investigate the use of active and passive microwave remote sensing techniques because it was clearly seen that an all-weather, day-or-night capability of observing ice and snow was essential. At about the same time, microwave technology advanced. Thus, the situation was ripe for making progress, and the 1970's indeed became a decade of great advances in snow and ice remote sensing. This paper presents a review of this work.

In February 1979, NASA's office of Space and Terrestrial Applications formed the Ice and Climate Experiment (ICEX) Science and Applications Working Group to consider the snow and ice research and operational needs of the mid-1980's in relationship to the potentially available satellite remote sensing capability. This working group produced a comprehensive and detailed plan which was published by NASA in December 1979 as the ICEX Report. This report calls for a program of coordinated investigations of the ice and snow masses of the Earth. These investigations are to be carried out using satellite, aircraft, and surface observations that will obtain information hitherto unavailable. Measurements derived from these investigations will be applied (1) to an understanding of the role of the cryosphere in the system that determines the Earth's climate, (2) to a better prediction of the responses of ice and snow to climatic change, (3) to studies of the basic nature of ice forms and ice dynamics, and (4) to the development of operational techniques for assisting such activities in the polar regions as transportantion, exploitation of natural resources, and, in temperate regions, the forecasting of snowmelt runoff.

The key to the success of the ICEX program will be the deployment of a set of four new microwave systems and one laser system on satellites flying high-inclination orbits; Large Antenna Multifrequency Microwave radiometer; Wide-Swath Imagery Radar; Scatterometer; Radar Ice Elevation Altimeter System; Laser Ice Elevation Altimeter System. The near-simultaneous observations of multiple ice and snow parameters by complementary sensors are needed for many cryospheric processes to be studied. Research on these fundamental processes has been data-limited, not idea-limited. These new remote sensing tools could enable us to discover in one decade as much as we have ever learned in the past about ice and snow.

SEA ICE

Before the first microwave imager was flown on Nimbus-5 in December 1972, several field experiments on the microwave properties of sea ice had already been made. An Electrically Scanned Microwave Radiometer (ESMR), for example, was taken to the Arctic on board the NASA "Galileo-1" Convair-990 Aircraft prior to being flown on Nimbus-5, as part of two expeditions in the Beaufort Sea involving aircraft and surface measurements from drifting ice stations.

Every new satellite microwave experiment on Nimbus-5, -6, and -7 Skylab GEOS-3, and Seasat-1 has been coupled with intensive surface and aircraft sea-ice expeditions. Since 1969, numerous minor and major international expeditions have included coordinated surface, aircraft, and satellite observational programs for the purpose of testing passive and active microwave techniques for remote sensing of ice. There have been five major expeditions: (1) AIDJEX (Arctic Ice Dynamics Joint Experiment) Spring 1971, 1972, and Spring 1975 through Spring 1976 - Main Experiment; (2) BESEX (Joint U.S./ U.S.S.R. Bering Sea Experiment, Spring 1974; (3) Skylab Snow and Ice Experiment--Winter-Spring 1973 and 1974; (4) SURSAT (Canadian Surveillance Satellite Experiment) Winter-Spring 1978 and 1979; (NORSEX (Norwegian Sea Marginal Ice Zone Experiment) Autumn 1978 and 1979.

The passive radiometers quickly showed the value of microwave techniques for ice research. Within 2 weeks of the launch of Nimbus-5 in December 1973, the ESMR provided the first synoptic views of the entire polar sea-ice cover. The data from this one sensor, which greatly exceeded its design lifetime by operating for more than four years, have permitted ice scientists to make several breakthroughs in the remote sensing of sea ice and ice sheets. These breakthroughs include the ability to distinguish sea ice from water, multi-year ice from first-year ice, and ratios of the mixtures of these two ice types. Ice concentrations (percentage of ice vs percentage of water per area) can be measured on hemispheric scales to an accuracy of 15 percent. Because the Nimbus-5 ESMR mapped the entire Arctic and Antarctic sea-ice packs every three days, it was possible to use the four-year data set to study sea-ice extent, the distribution of multiyear and first-year ice, and ice concentration variations at time scales ranging from several days to seasonal to annual.

To aid in the analysis of this large data set, time-lapse films were made of the Arctic and Antarctic sea-ice packs, enhancing the study of several ice phenomena such as the complex structure and dynamics or marginal ice zones, and the growth, motion, and decay of large areas of reduced ice concentration (polynas) that occur within the Arctic pack in all seasons.

The scanning Multichannel Microwave System (SMMR) flown on Nimbus-7 and Seasat has provided the first multifrequency, multipolarized passive microwave data of sea ice. Although the SMMR gives the ice data at the same resolution as the ESMR (25 kilometers), it must be viewed as a significant advance because it allows a far more accurate measurement of key ice phenomena. For example, the recently completed ice retrieval algorithms indicate that sea ice concentration can be measured to an accuracy of 5 percent, a significant advance compared to the 15 percent accuracy of ESMR.

Another new active microwave sensor recently flown in space for the first time has also yielded exciting sea-ice data. It is the Synthetic Aperture Radar (SAR) on Seasat-1. An assessment of some of the optically processed SAR images shows that we now have the ability to acquire high-resolution, all weather, day-or-night synoptic-scale observations of sea ice and of ocean-surface phenomena. Despite the early demise of this satellite, sufficient ice data were acquired to show that the SAR is a unique tool for studying sea-ice morphology and dynamics at various space and time scales.

Several sea-ice dynamics models exist, but there are insufficient data with which to develop and test these models properly. A key requirement for understanding sea-ice dynamics is to map accurately and frequently the location of sea ice on synoptic scales together with the wind stress field. Sea ice images taken daily for selected periods with a typical spatial resolution of 50 to 100 m are needed. Not only must this high resolution be attained, but it is necessary to be able to locate geographically each pixel of a given radar image to the 100-200 m level of accuracy. Recent analysis of digitally processed Seasat SAR images of the Beaufort Sea shows that this pixel location accuracy is attainable. A spaceborne radar similar to that flown on Seasat-1 is the only known way to acquire this high-resolution, large-scale imagery at the time rate demanded.

ICE SHEETS

The large ice sheets of Antarctica and Greenland are not only indicators of climatic anomalies, but they are sufficiently massive (they contain 85 percent of the fresh water on earth) to interact with climate and influence its course. In order to understand what is now happening to these ice sheets - how they have responded to, or perhaps caused, major climatic changes and how to predict what they will be doing in the future - we must first be able to measure their surface and basal configurations and determine whether the total volume of ice at present is increasing, decreasing, or remaining constant. Analysis of the first satellite radar altimeter measurements of Greenland acquired by the GEOS-3 satellite demonstrated that space borne microwave techniques could be used to map ice sheet topography to hitherto unattainable accuracies. The GEOS-3 data were used to map the surface topography of southern Greenland to an accuracy of approximately two meters, one to two orders of magnitude better than earlier measurements. Theoretical work has shown that a similar increase in the accuracy of the ice-sheet bedrock topography could be obtained by a satellite-borne radio echo sounder. It has been shown that Nimbus-5 ESMR imagery can be used to determine ice-sheet accumulation rates. The Nimbus-7 and Seasat SMMR data will provide the first look at the multispectral time-dependent variations of the ice-sheet surface microwave emissivities and will yield a more accurate estimate of snow accumulation rates.

Considering these recent advances in the microwave remote sensing of ice sheets, the ICEX report stressed that a unique opportunity for monitoring ice sheets now exists and that the ICEX instrument ensemble could do the job.

In view of the general worldwide warming expected in the next few decades and the effect this will undoubtedly have on ice sheets, it is clearly of the utmost importance to begin monitoring their behavior immediately. Our present knowledge of ice sheets is so incomplete that we cannot predict whether they will surge or break up, will shrink because of faster melting at their edges, or will grow because of increased snowfall in their interiors. However, the ability to monitor ice-sheet topography to the one-meter level of accuracy, attainable with the ICEX instrument ensemble, would make possible the detection of an ice volume change that would correspond to a 3-4 cm sea-level change. This would enable an early warning to be issued to the world on the trend in ice-sheet variation and sea-level change.

SNOW

At its maximum extent in January, seasonal snow covers an area considerably greater than that of all sea-ice packs and continental ice sheets combined. The importance of snow cover to the heat balance of the earth, including the possibility of a positive feedback, has been recognized for a long time. However, it wasn't until the advent of satellite observations that it was possible to obtain the data needed for quantitative studies.

Data from visible sensors flown on the ESSA, ITOS, and NOAA satellites have been used to map snow-cover extent and variations. For the shorter time scales (day to week) there are still some problems of differentiation between clouds and snow. The only means available to observe snow-pack hydrological properties from space is by microwave techniques, and in the last decade this field of research has received considerable attention. Low-frequency micro-waves have the snow-penetrating capabilities which enable the internal characteristics of snow to influence the micro-wave signature. Observation of snow-covered regions have been made with the ESMR's on board the Nimbus-5 and 6 satellites.

Several other passive microwave studies have addressed (a) the theoretical estimation of microwave emission from snow, (b) comparison of model calculations with satellite-observed T_B's from polar firn, (3) snowfield thermodynamic temperature, (d) determination of crystal size by the use of multifrequency microwave radiometer measurements, and (e) correlation estimation of microwave emission to water equivalent, depth, and free water content.

For dry snow conditions on the high plains, significant relationships between snow depth or water equivalent and microwave T_B were developed. A flat, relatively homogeneous area of ESMR field of view was necessary for the dry snow study because the ESMR surface resolution was coarse. Thus, the estimation of snow depth under dry snow conditions is possible and feasible. Further data sets are needed to extend the relationship over a greater range of snow depth.

The presence of melt water in the snowpack radically changes the microwave emission characteristics--resulting in as much as 35 K increases in T_B over dry snow conditions. Such changes allow easy detection and monitoring of melting snow pack, and the estimation of the timing of snowmelt runoff. Ground truth for such microwave experiments from space might be obtained from low altitude gamma ray techniques, which are useful for obtaining snow-water equivalent over a snowfield within the satellite field of view.

The proposed ICEX instrument ensemble would provide unique data for snowpack research. Analysis of the ICEX data set would focus on a comparison of the multispectral radiometer and scatterometer data with the area-wide ground-truth data in order to verify previously established snow mass and brightness temperature relationships.

Results from such a study should answer the following questions: how well can snow mass be estimated?; can snow parameter versus brightness temperature relationships be transferred between various areas?; what sensor ensemble would provide the best data for operational monitoring of snow distribution?