GLACIOLOGICAL DATA

REPORT GD-24

PASSIVE MICROWAVE RESEARCH
MICROWAVE BIBLIOGRAPHY UPDATE 1988-1991

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Ann M. Brennan

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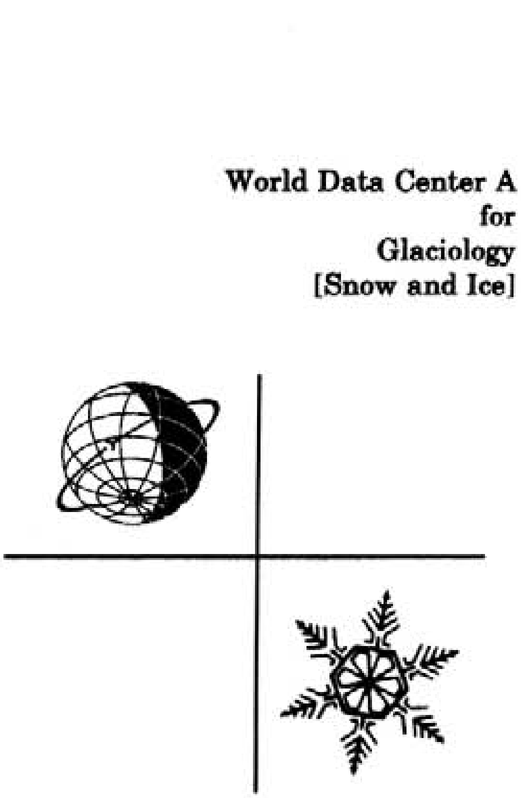

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DESCRIPTION OF THE WORLD DATA CENTER SYSTEM[1]

The World Data Centers (WDCs) were established in 1957 to provide archives for the observational data resulting from the International Geophysical Year (IGY). In 1958 the WDCs were invoked to deal with the data resulting from the International Geophysical Cooperation 1959, the one-year extension of the IGY. In 1960, the International Council of Scientific Unions (ICSU) Comite International de Geophysique (CIG) invited the scientific community to continue to send to the WDCs similar kinds of data from observations in 1960 and following years, and undertook to provide a revised *Guide to International Data Exchange* for that purpose. In parallel the CIG inquired of the IGY WDCs whether they were willing to treat the post-IGY data; with few exceptions, the WDCs agreed to do so. Thus the WDCs have been serving the scientific community continuously since the IGY, and many of them archive data for earlier periods.

In November 1987 the International Council of Scientific Unions (ICSU) Panel on World Data Centers prepared a new version of the *Guide to International Data Exchange*, originally published in 1957, and revised in 1963, 1973 and 1979. The new publication, *Guide to the World Data Center System, Part 1, The World Data Centers (General Principles, Locations and Services)*, was issued by the Secretariat of the ICSU Panel on World Data Centers. This new version of the *Guide* contains descriptions of each of the twenty-seven currently operating disciplinary centers, with address, telephone, telex, and contact persons listed. The reader is referred to the new *Guide* for descriptions of the responsibilities of the WDCs, the exchange of data between them, contribution of data to WDCs, and the dissemination of data by them. The WDCs for Glaciology are listed below.

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Chinese Academy of Sciences
Lanzhou 730000, China
Telephone: (86)0931-26725, ext. 308
Director: Professor Xie Zichu

The following organization provides international data services including data analyses and preparation of specialized data products. It merges the previous activity of the Permanent Service on the Fluctuations of Glaciers and the Temporary Technical Secretariat for World Glacier Inventory. These activities are not part of the WDC system but the center cooperates with WDCs in the discipline. Users wishing assistance in seeking data or services from this group may contact an appropriate WDC.

World Glacier Monitoring Service (WGMS)

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[1] Adapted from *Guide to the World Data Center System. Part 1. The World Data Centers (General Principles, Locations and Services).* International Council of Scientific Unions. Panel on World Data Centers, November 1987, 91pp.

FOREWORD

This report provides an update of the bibliography on passive microwave research relating primarily to snow and ice, meteorology, oceanography and the land surface published in *Glaciological Data, Report GD*-19 in 1987. Some 600 citations are listed by author and subject area.

Short contributions are also included from the staff of the Data Center and colleagues in the Division of Cryospheric and Polar Processes, CIRES. The data management activities of WDC-A for Glaciology benefit considerably from this infusion of experience based on research use of the data products and work contributing to their validation and improvement. These local scientists also provide a direct link to the general research community who help considerably in the development of research-quality data products.

We welcome your comments on this bibliography and suggestions for future *GD* reports. The decreased frequency of their publication in recent years reflects an insufficiency of general funds for that purpose rather than any lack of ideas or interest at the Center. We acknowledge the support of the National Aeronautics and Space Administration (contracts NAGW-1839 and NAGW-641) which facilitated publication of this issue.

Thanks are due to Ann M. Brennan for her editing and compilation of the bibliography and Carol Pedigo and Margaret Strauch for word processing support.

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PASSIVE MICROWAVE BIBLIOGRAPHY

Cryospheric Products from the DMSP-SSM/I

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Introduction

The polar regions are an important component of the global climate system. They are the primary sink for energy transported from lower latitudes by the atmosphere and oceans. Feedbacks involved in the interactions between the cryosphere and the atmosphere serve to amplify climate perturbations in high latitudes, where much of the deepwater for the world oceans is formed. Seasonal variations in sea ice cover in the Arctic Ocean play a significant role in its freshwater balance. Climate observations and models demonstrate the sensitivity of polar regions to global climate change, yet the representation of polar processes in general circulation models is still inadequate.

Satellite remote sensing has played an increasingly important role in the study of polar regions over the last two decades, given the sparse network of ground observing stations and the problems caused by the severe environment. Passive microwave data have significant advantages because they are not limited by solar illumination conditions and, at low temperatures, atmospheric moisture has only a small effect on the microwave emission received by the sensor.

The Passive Microwave Record

Data on polar sea ice have been collected more or less continuously since 1973, providing the basis for a consistent view of global ice extent and its annual and interannual variations. Single channel (1.55 cm) passive microwave radiometers were operated on Nimbus 5 and 6 (1973-76), Scanning Multichannel Microwave Radiometers (SMMR) on Seasat (1978) and Nimbus 7 (1978-87), and a similar instrument on the polar orbiting Defense Meteorological Satellite Program (DMSP) F-8 platform (since June 1987). The DMSP provides the first operational measurements from the Special Sensor Microwave Imager (SSM/I) which will be flown on future DMSP satellites during the 1990s. The earlier sensors were designed for research and development purposes. Technical details on the SSMR and SSM/I instruments are summarized in Table 1.

Table 1. Characteristics of the SMMR and SSM/I sensors. (From *Barry*, 1991.)

Sensor	Wavelength (cm)	Instantaneous field of view (km)
SMMR	4.6	150
	2.8	100
	1.7	55
	1.4	45
	0.81*	30
SSM/I		
	1.55	70 x 45
	1.35*	60 x 40
	0.81	38 x 30
	0.35	16 x 14

*Vertically polarized only.

Data Management at NSIDC

A plan to process, archive, and distribute sea ice products from passive microwave measurements obtained from the SSM/I was initiated in 1982. NASA's Polar Oceans Program established a Science Working Group to consider the scientific uses of the SSM/I data for sea ice research and to define the requirements for data products. The group's recommendations (*NASA*, 1984) resulted in a decision to adapt the Pilot Ocean Data System (now NASA Ocean Data System, NODS), developed at the Jet Propulsion Laboratory (JPL), as the basis for the data processing system. A cooperative project between JPL-NODS and the National Snow and Ice Data Center (NSIDC) led to the development at NSIDC of a centralized minicomputer - based system employing DEC-VAX processors in a cluster environment (*Weaver et al.*, 1987). However, the rapid development of workstation systems and the availability of compact discs (CD-ROMs) as a viable distribution medium resulted in a restructuring of the data management system. The current system uses the central facility for data ingest, quality control, and the production of gridded data sets. Data extraction and image display are performed by users who receive the CD-ROMs through utilization of software provided for AT-class personal computers.

Data Products

NSIDC currently receives SSM/I antenna temperature swath data on tape via Remote Sensing Systems Inc. These are converted to brightness temperatures, screened for transmission errors, and stored on 12-inch optical platters (2 gigabytes per platter) in a Rapid Access Archive (RAA). Gridded brightness temperature fields are generated from the RAA on polar stereographic grids with an origin at each pole and a standard latitude at 70 degrees (Figure 1). One grid contains the 0.35 cm data, a second grid the brightness temperatures of the other three channels (Table 1), and a third will contain sea ice concentrations calculated using the NASA Science Working Group Algorithm, following the final report of the NASA SSM/I Sea Ice Algorithm Validation Team.

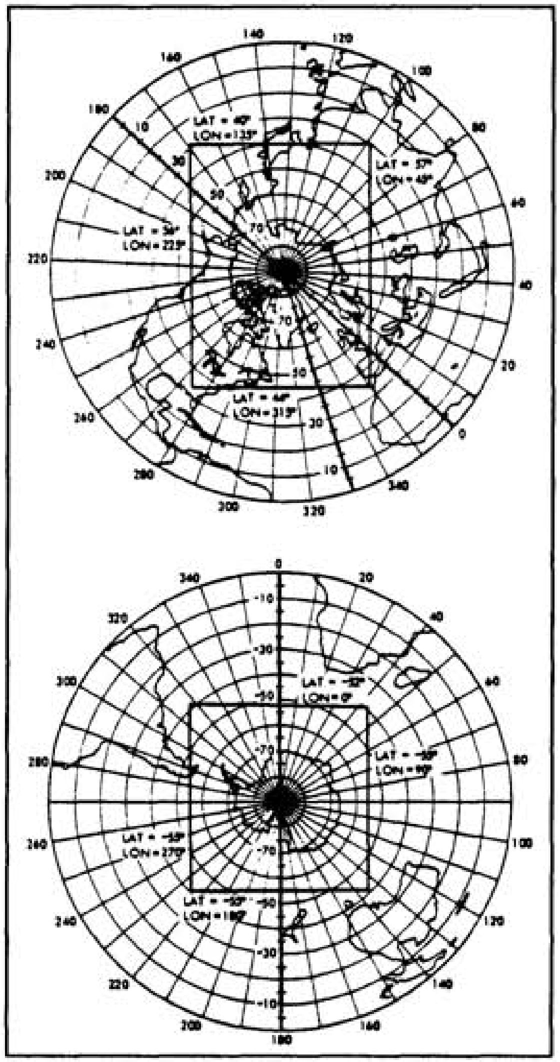

Figure 1. Geographical areas in the Northern and Southern Hemispheres covered by the SSM/I grids.

As of November 1991, eleven CD-ROMs, each containing approximately three months of data, have been released for the period 9 July 1987 - March 1989. Details of the grid structure and contents are provided in a *User's Guide (NSIDC,* 1990). Concomitant distribution of a questionnaire indicates that over 90 percent of users would like more SSM/I data on CD-ROM, and almost 80 percent requested SMMR data to be released (in the same format) on CD-ROM. There is also considerable interest in adapting the CD-ROM product to Macintosh, SUN and VAX CPUs.

The NSIDC will also produce test products for snow cover from the SSM/I data. An SSM/I Products Working Team has been established with support from NASA to intercompare existing algorithms for snow extent and water equivalent and to recommend suitable ones to be adopted by the NSIDC. Several studies have demonstrated that it will be necessary to use an algorithm that is regionally and seasonally specific and that incorporates adjustments for forest cover and topography.

Research

The use of passive microwave data for research into cryosphere/climate-related problems currently underway at the National Snow and Ice Data Center is discussed in subsequent papers. These address algorithm validation, process studies, and questions of temporal variability and global change.

Concluding Remarks

The record of sea ice extent and concentrations is short. Another decade of passive microwave measurements, consistent with those from SMMR, will become available from the DMSP SSM/I during the 1990s to provide a basic climatology. It is important that these products and the algorithms on which they are based be carefully scrutinized. Similar efforts are beginning to test appropriate products from SSM/I snow cover parameters through a NASA-supported SSM/I Products Working Team. The work conducted at NSIDC as part of these studies will also lay a foundation for the future development of snow and ice products to be derived from the instruments to be flown on the Earth Observing System (EOS) Polar Platforms in the late 1990s.

Acknowledgment

This work has been supported by NASA grant NAGW-641 to the University of Colorado.

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Passive Microwave Data for Snow Cover Studies at NSIDC

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Snow cover is an important variable for climate and hydrologic models due to its effects on energy and moisture budgets. A primary factor controlling the amount of solar radiation absorbed at the earth surface is the extent of snow cover due to its high albedo. Any decrease in snow cover resulting from a warming trend results in increased absorption of solar radiation and additional heat to melt increased amounts of snow. This results in the classic positive temperature-albedo feedback mechanism which is included in nearly all climate models. In addition to the albedo effect, snow cover represents a significant heat sink during the warming period of the seasonal cycle due to a relatively high latent heat of fusion. As a result, the seasonal snow cover provides a major source of thermal inertia within the total climate system as it takes in and releases large quantities of energy with little or no fluctuation in temperature. Therefore, snow cover is an important variable for global climate monitoring and change detection.

During the past two decades much important information on hemispheric-scale snow extent has been provided by satellite remote sensing in the visible wavelengths (*Robinson et al.*, 1991; *Dewey*, 1987). One major problem with the application of visible wavelength data is the need for clear sky conditions. Persistent cloud cover in winter may limit data to only a few days per month. In addition, visible-band data do not provide the opportunity to extract snow water equivalent or depth information.

Passive microwave remote sensing offers several advantages over visible-band data. It is currently the best method to monitor temporal and spatial variations in snow cover on hemispheric to global scales. Passive microwave remote sensing allows data collection in nearly all weather conditions and during darkness, and also provides the potential to compute snow water equivalent and to detect melt (*Kunzi et al.*, 1982; *Foster et al.*, 1984; *Rott*, 1987; *Rango et al.*, 1989). These additional variables comprise important input to energy budget, hydrologic, and global circulation models.

Microwave energy emitted from the surface of the earth is measured by the Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave Imager (SSM/I) which provides data in four separate channel frequencies (*Weaver et al.*, 1987). SSM/I coverage is global and frequent, at least daily for locations north of about 43 degrees north latitude, and once every two to three days for those areas where snow might be expected south of 43 degrees. When snow covers the ground, some of the microwave energy emitted by the underlying soil is scattered by the snow grains. When moving from snow-free to snow-covered land surfaces, a sharp decrease in emissivity provides a nearly unambiguous indicator of the presence of snow. The amount of scattering is related to both the amount of snow (number of grains) and specific wavelength. Based on this relationship, algorithms have been developed which indicate the presence of snow and compute snow water equivalent, or snow depth, given an assumed density (*Chang et al.*, 1981; *Chang et al.*, 1987a and b; *Kunzi et al.*, 1982; *Hallikainen and Jolma*, 1986; *McFarland et al.*, 1987; *Goodison*, 1989; *Aschbacher*, 1989; *Josberger et al.*, 1990; *Rott et al.*, 1991; *Grody*, 1991).

There are also disadvantages to the passive microwave data. The resolution is poor compared to that typically available from visible-band sensors (*Rott*, 1987). Resolution depends on the channel frequency and is approximately 30 km for those channels used in the snow cover algorithms. In addition, the application of passive microwave is limited to dry snow. Once liquid water is present on the ice grains, the snow surface becomes a strong emitter and is indistinguishable from bare ground. This dramatic change in signal can be used to monitor the onset of melt, but as long as the snow is wet, its location and water equivalent cannot be determined using SSM/I data alone. If the snow refreezes, it again become "visible" to the microwave sensor. Another problem results from the fact there may be objects which are primarily emitters which extend above the snow cover, such as dense coniferous forests or bare rock outcrops. The increased emission from such surface features will tend to reduce the total amount of scattering integrated across the pixel and thus may indicate a lesser amount of snow cover than is actually present.

Finally, there are complications which result from the snow structure itself. The amount of microwave scattering is not only dependent on the number of grains, but also on the size of the grains, the larger the grains the greater the scattering. In theory, brightness temperature is very sensitive to grain size *(Chang et al.*, 1981). In order to make any practical use of a given algorithm, the snow grain diameter to within about 0.2 mm would be required. Except for local scale studies, it is simply not feasible to obtain such detailed snow structure information. However, when existing algorithms are tested the results do not show such a high degree of sensitivity to grain size. Algorithms which assume a single grain size provide reasonable results on the regional scale (*Chang et al.*, 1987b; *Kunzi et al.*, 1982; *Aschbacher*, 1989; *Goodison*, 1989; *Hallikainen and Jolma*, 1986). Apparently the shapes of the natural snow grains are not as sensitive to scattering as the spheres used in the radiation transfer theory. In addition, for regional scale studies, it appears that only the mean grain size may be required and not the detailed layer by layer structure of the snow cover. Although not as sensitive as theory might indicate, testing has shown that algorithms which assume a single grain size (for example, 0.6 mm diameter, *Chang et al.*, 1987b) do eventually produce unreasonable values when the mean grain size of the snow cover exceeds about 2.0 mm in diameter (*Armstrong*, 1990b; *Hall et al.*, 1986).

As long as the snow cover remains sub-freezing there is only one process, temperature-gradient or kinetic metamorphism, which will cause the mean grain size of a layer to exceed a diameter of 2.0 mm (*Armstrong*, 1985; *Colbeck*, 1991). Using a relationship between average snow depth for a given region and current depth and temperature data, we are investigating a method which will identify the conditions which result in a snow cover with a mean grain size larger than 2.0 mm. Given this information, a technique to adjust the microwave algorithms for grain size can be provided (*Armstrong et al.*, 1991).

NSIDC is currently involved in two specific projects which apply passive microwave remote sensing data to the study of snow cover. The first project is funded by NASA's Interdisciplinary Research Program to develop a capability for the production of daily snow parameter products from the DMSP SSM/I. A data system is being developed which will produce, archive, and distribute validated snow cover products for community use. Initial emphasis is on Northern Hemisphere snow extent. We are also exploring the potential of the SSM/I for mapping other snow cover properties such as snow water equivalent, snow depth, and dry/wet snow boundary (*Armstrong*, 1990a).

Within this project NSIDC coordinates the activities of the SSM/I Products Working Team (SPWT) which is a multi-agency and multi-disciplinary working group focussing on the problems associated with extracting land surface (primarily vegetation, soil, and snow cover) information from SSM/I. Currently, emphasis is on developing optimal binning and gridding routines as well as the selection of one or more snow cover algorithms for use in the distribution of standardized data sets by NSIDC. Snow cover algorithm comparison is being undertaken in a cooperative effort with scientists at the University of Innsbruck, Austria (*Rott et al.*, 1991), the Canadian Climate Center (*Goodison*, 1989), and NASA Goddard Space Flight Center (*Chang et al.*, 1987a and b; *Chang et al.*, 1991). Regional test areas selected are the western United States, central Canada, and Europe. In the U.S., the accuracy of the algorithms is being tested by comparison with several validation data sets including snow depth measurements from the National Weather Service and the Soil Conservation Service, as well as output from the prototype Air Force Global Weather Central (AFGWC) snow depth model described below. Later stages of this project will explore the combined research potential of SSM/I-derived snow cover and sea ice products for climate dynamics and global/regional hydrology.

The second NSIDC project utilizing passive microwave data involves the development of a prototype snow depth model to replace the current model used by the U.S. Air Force Global Weather Central (AFGWC) (*Armstrong and Hardman*, 1991a and b). The initial goal of the project was to analyze weaknesses in the current version of the model, identify enhancements, and design and demonstrate an improved software system. The prototype model which was completed in 1991 provides a state-of-the-art integration of all snow cover data available at AFGWC in order to provide a global snow cover product at a 40 km grid resolution. The basic data generated for each grid point include calculated average and maximum snow depth, age in days of the total snow cover, and days elapsed since the last snowfall, along with appropriate data source flags and summary diagnostics. The model represents the integration of surface and satellite observations. Surface measurements used are from the World Meteorological Organization (WMO) synoptic data collection network. In locations where surface measurements are inadequate, the model applies algorithms which rely on SSM/I data to provide snow cover extent and information on snow depth. Because no single snow depth algorithm is suitable for global scale application, NSIDC is evaluating individual algorithms, as described above, to determine which are most accurate for a given surface-type condition.

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Artificial Intelligence Applications of Arctic Passive Microwave Data

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Introduction

The use of artificial intelligence (AI) methods in remote sensing and the geosciences is increasing, and systems are being developed routinely for image classification. Knowledge-based (or rule-based or "expert") systems (KBS) and neural networks may be useful for the retrieval of geophysical parameters from satellite data because of their relatively simple yet flexible structures. Knowledge-based systems are an efficient and flexible way of encoding knowledge as "if-then" rules, without being bound to traditional sequential processing modes. Processing may occur numerically or symbolically, and is controlled by the type of data available. The popularity of neural networks can be attributed to their ability to combine numeric and symbolic information (like knowledge-based systems), to accept degraded and even interrupted input streams, and to produce "fuzzy" output, alleviating some of the problems inherent in hard classifiers.

For sea ice research using passive microwave data, both KBSs and neural networks have been employed only in an exploratory sense. For example, a neural network has been developed that is capable of classifying passive microwave data into ice seasons consisting of winter, pre-melt, and melt onset periods (*Maslanik et al.*, 1990). In that study, all five channels of the Scanning Multichannel Microwave Radiometer (SMMR) were utilized in a time series in the Beaufort Sea. The performance of the network was evaluated by comparing the resulting spatial and temporal patterns to visible-band imagery, surface albedo maps, and to drifting buoy meteorological data. Since the network output for each season is in the range (0,1), it represents, in a conceptual (but not theoretical) sense, a probability and reflects the uncertainty in the signature at the transition between seasons. A KBS for the detection, mapping, and statistical analysis of sea ice leads is described in *Key et al.* (1990). While the system utilizes Landsat rather than passive microwave data, the basic framework is suitable to other sea ice parameter retrievals. Individual lead fragments are identified and labeled with a region-growing procedure, then a set of rules is applied to generate hypotheses regarding the likelihood that each belongs to a lead system. Numeric procedures are invoked as rules are fired in order to determine various statistical and geometric properties of the lead fragments. Results indicate that the resulting leads and their derived width and orientation statistics are similar to those determined through manual interpretations. Additional ongoing studies of artificial intelligence applications utilitizing passive microwave data are now described.

Classification of Merged AVHRR and SMMR Data with Neural Networks

The Arctic region provides a unique set of problems for image analysis algorithms. Current procedures for automated analyses of satellite radiance data have been developed for low and middle latitudes but their application to polar regions has been largely unexplored. Those that have been applied often fail in the polar regions because surface temperatures are commonly as low or lower than cloud-top temperatures, and because snow-covered surfaces exhibit albedos similar to those of clouds. Also, extremely low surface temperatures and solar illuminations cause satellite radiometers to operate near one limit of their performance range. Because of these problems, a complex analysis method is necessary. The ability of neural networks to extract four surface and eight cloud classes in the Arctic from a merged data set consisting of five Advanced Very High Resolution Radiometer (AVHRR) and two SMMR channels has been and is continuing to be investigated (*Key et al.*, 1989). The AVHRR visible and thermal data were used for cloud analysis while the SMMR data were used to provide additional information about the surface beneath the clouds, especially sea ice.

The neural network was trained on hundreds of pixels, where the AVHRR and SMMR radiances constitute the input and the correct surface/cloud class for each pixel is the output. Results are compared to manual interpretations and to output from a supervised classification with a maximum likelihood class assignment scheme. The differences between the neural network and the supervised maximum likelihood classifications were primarily due to the greater flexibility of the neural network to classify indistinct classes, e.g., classes containing pixels with spectral values that differ significantly from those in the training areas, while ignoring assumptions of statistical normality. The two classification approaches illustrate the tradeoffs between human interaction in the selection of training areas and classification accuracy and flexibility.

The neural network approach to classification is generally less rigid than the traditional maximum likelihood procedure in that: 1) there are no assumptions of distributions of variables and relationships between them; 2) the network is easily trained to learn the relationships between input and output; and 3) the classification produces both a categorical value and a type of membership value for each pixel. It is recognized that there is some loss of information and interpretability with the departure from statistical theory. Additionally, computation time required for training the network is not trivial when compared to the training of the maximum likelihood classifier (i.e., computation of mean vectors and the covariance matrix), although future hardware architectures should alleviate this problem. Of course, training time as a proportion of the total classification time decreases with the amount of data processed, so that if classes do not change and large images are being classified, overall processing time should be similar for both methods.

The ability to interpret weights within the trained network provides a potentially powerful tool for understanding the role of inputs and the geophysical processes they represent in the making of decisions. Through an examination of the connection strengths between input, hidden, and output units, it is possible to identify which inputs influence the classification most, and which are redundant. As shown in Figure 1, these relationships are not always clear, and care must be taken in extending their interpretation to physical processes. It was observed in the weights, however, that the passive microwave data plays an important role, albeit indirectly, in the identification and classification of polar clouds in satellite data. This fact was also exploited in a more traditional approach to cloud detection in *Key and Barry* (1989).

Sea Ice Research with Expert Systems and Neural Networks

Several methods exist that may improve the retrieval of ice concentrations, including the use of local tie-points, corrections to reduce atmospheric attenuation and the effects of surface winds on open water, incorporation of ancillary data such as surface temperature, utilization of region-specific procedures, and the assimilation of observations with a physical model. The underlying theme of each of these approaches is that additional sources of information exist that can be used to reduce the uncertainty in ice classification. While methods such as the Kalman filter provide a means of combining data types, a more flexible unifying framework that allows for rapid algorithm prototyping is needed. Knowledge-based systems and neural networks provide such a framework.

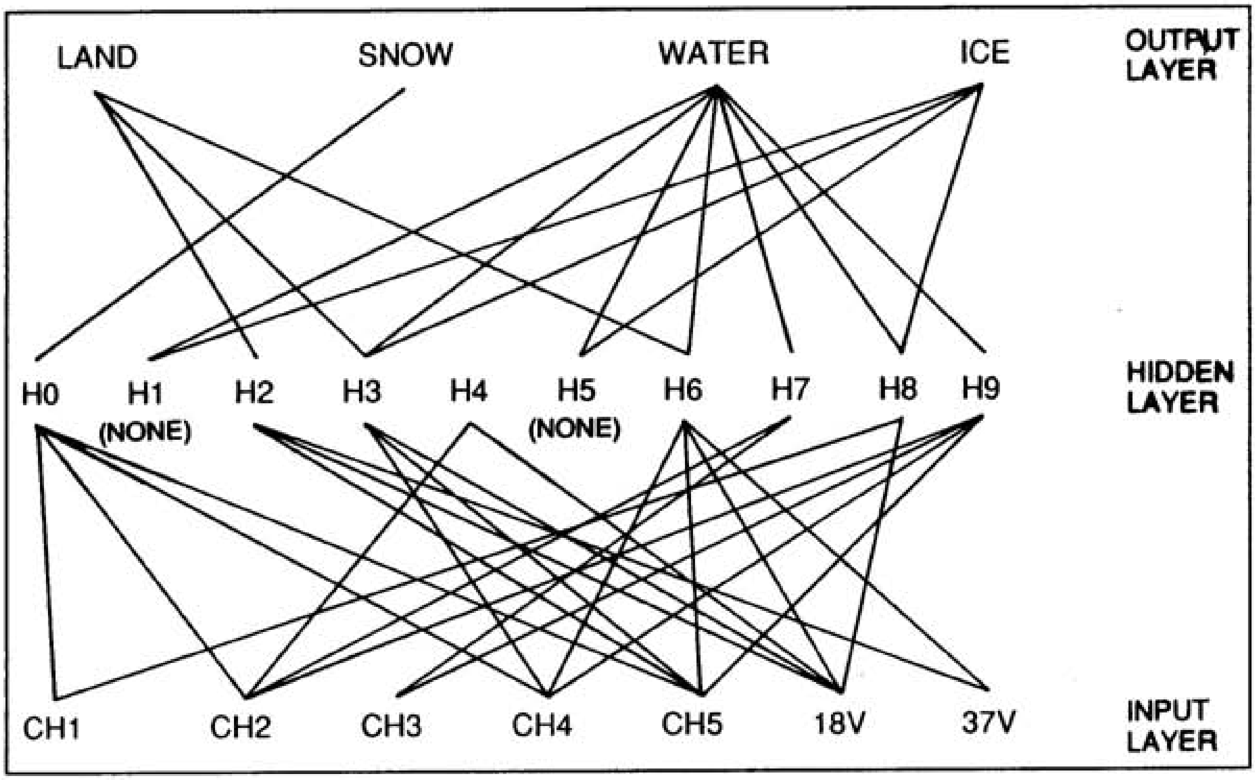

Figure 1. Connections between the input channels, hidden layer neurons, and the output classes in the neural network trained for image classification. Only surface output classes are shown. Input needs represent the five visible and thermal AVHRR classes and two SMMR passive microwave channels.

For the retrieval of sea ice concentration from passive microwave data, two algorithms are currently under development, a KBS and a neural. The neural network structure follows that of the Kalman filter, taking advantage of the temporal dependence of the ice signatures to reduce the ambiguity in the passive microwave signal particularly during the summer. A physical model that describes the way in which ice concentration changes over time is an integral part of the network. Input includes brightness temperature observations, fractional coverages of each surface type estimated by a physical model (open water, first-year and multi-year ice), and time of year. The prototype network is trained with simulated observations based on assumed true ice fractions; monthly pure signatures for a single microwave channel and each of the surface types are combined with the fractional coverage of each surface and a random error based on the variability of the pure signatures (time and surface dependent). An inherent error that accounts for the unmodeled physics in the physical model is assumed. An arbitrarily complex model can be used without change to the network, except for the specification of the model error. Preliminary results indicate that the network, like the Kalman filter, acts as a smoothing filter, reducing the influence of extreme brightness temperatures that correspond to, for example, summer melt.

The KBS design for sea ice concentration retrieval consists of a set of modules to handle input, data checking and validation, classification, and certainty assessment. The NASA Team Algorithm is the core of the classification step. The KBS is a controller and source of knowledge that supplies appropriate inputs to the algorithm, and monitors the algorithm output in light of the time of year and geographic area. Inputs include brightness temperatures and meteorological data. The rule base is used to impose boundary conditions based on season and location upon the ice classification, to determine when observed conditions indicate a potential problem situation (e.g., weather effects, melt), to develop confidence levels for the classified data, and to attempt to improve the classification by invoking correction schemes or by supplying realistic information for classification such as tie-points or probabilities of new ice growth. Results to date show an improvement in ice concentration estimates over the Team Algorithm alone, particularly during the summer months when surface melt and weather effects are at their maximum. However, weather effects in particular are still a problem, and the KBS will be extended to include additional atmospheric measurements of cloud and water vapor from, for example, AVHRR and TOVS.

Conclusion

The AI research described here has been largely exploratory, with the goal of examining the feasibility of these methods in the context of sea ice parameter retrieval from satellite data. Overall, knowledge-based systems and neural networks show promise, although there are inherent problems. Neural networks, for example, are essentially "black boxes" that may perform remarkably well but for unknown reasons. The weights on the connections between input, hidden, and output nodes are difficult if not impossible to decipher, especially when the number of nodes is large. Knowledge-based systems are more transparent, but the sequence of operations, being data driven, is not easy to predict. There are no claims that KBSs or neural networks provide the final solution to the types of problems described above. What they do provide is a framework that is flexible enough to allow for rapid prototyping of systems that include a diverse set of input variables for a complex, and possibly poorly specified, problem.

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Passive Microwave Data for Climate Interactions Studies

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Passive microwave data provide valuable information about sea ice concentration and ice extent and, with a lower degree of confidence, multiyear ice percentage (e.g., ice that has survived at least one melt season). Research currently underway within the Cooperative Institute for Research in Environmental Sciences, Division of Cryospheric and Polar Processes (CIRES, CPP) seeks to apply this information to improve our understanding of the short-period response of the ice pack and associated changes in energy fluxes and new ice growth. In addition, we are continuing to investigate ways of improving the retrieval of geophysical information from the microwave data by assessing the effects of changes in surface and atmospheric conditions not related to ice concentration or ice type.

Applications for Atmosphere-Ice-Ocean Interactions

Our study of ice-atmosphere interactions has focused on statistical and modeling comparisons of microwave-derived ice conditions with atmospheric forcing fields such as winds and temperatures, and on the combination of ice concentrations with other information to calculate turbulent fluxes over large areas. *Barry and Maslanik* (1989) studied a six-year data set of Scanning Multichannel Microwave Radiometer (SMMR) data, Defense Meteorological Satellite Program (DMSP) Optical Linescan System (OLS) visible-and thermal-band imagery, and Advanced Very High Resolution Radiometer (AVHRR) data together with meteorological information from drifting buoys and Navy/NOAA ice charts to determine temporal and spatial scales of variability in ice concentration and extent in the western Arctic. Substantial, rapidly-forming reductions in brightness temperatures similar to those reported in earlier studies were identified in several years (*e.g., Gloersen et al.*, 1978; *Crane et al.*, 1982; *Campbell et al.*, 1984). Analyses of time series of brightness temperatures, AVHRR and OLS imagery, and atmospheric data lend strong evidence that the observed changes are, in fact, true reductions in ice concentration. Comparisons of brightness temperatures with temperatures measured by drifting buoys (*Maslanik and Barry*, 1988) point out the need to combine several sources of information, including other satellite imagery (*e.g., Maslanik et al.*, 1989) to reliably interpret ice conditions during melt periods. The observed rapid changes in concentration over large areas could significantly affect surface albedos, ice thickness, and brine generation as new ice forms. A region centered approximately along 155° west longitude in the Canada Basin showed a mean tendency for reduced concentrations in early autumn; rough calculations of new ice growth within a 40,000 km^2 area in this region for 1980-1983 show ice production ranging from 32.12 km^3 in 1982 to 7.17 km^3 in 1980 (*Maslanik and Barry*, 1990).

The atmospheric conditions that result in such changes in ice concentration have been investigated in several case studies. *Serreze et al.* (1990) calculated mean ice divergence based on drifting buoy vectors in the western Arctic, and found that the observed region of reduced concentrations in the Canada Basin corresponded to regions of higher mean ice divergence induced by low pressure systems persisting in the northern Canada Basin. *Maslanik and Barry* (1990) found that both persistent low pressure systems centered over the Basin, as well as the strong winds in the Canada Basin associated with highs and lows over the Canadian Archipelago and Laptev Sea, produced rapid reductions in concentration over regions generally aligned parallel to the geostrophic winds. *LeDrew et al.* (1991) examined the mechanisms that might interact to sustain lows in the Canada Basin and concluded that, while heat flux from the ice-ocean boundary enhanced due to the diverging ice pack had some regional effect on the synoptic pattern, conditions within the low pressure system itself had a larger effect. *Serreze et al.* (1990) compared output from the Polar Ice Prediction System (PIPS) model with OLS and SSM/I imagery for a particularly well-developed reduction in concentration in late summer 1988, and found evidence for several mechanisms that might have contributed to the observed changes in ice condition. Work is currently underway using a two-dimensional thermodynamic-dynamic ice model with modifications to the radiative and turbulent flux terms to help sort out the contributions of ice dynamics versus thermodynamics in the production of these reduced-concentration areas.

Investigations of Physical Processes and Algorithm Refinements

In addition to such applications of passive microwave data to climate studies, CPP scientists are working to better understand the data themselves, and how they interact with conditions such as surface melt, winds on the open ocean, presence of different ice thicknesses, and changes in atmospheric water content. In addition to allowing us to better understand and rely upon the performance of existing data classification schemes, understanding the physical interactions among these variables offers insights into ways to extract additional information from the imagery. One aspect of this work involves comparison of the passive microwave imagery to "validation" data such as Landsat imagery that, due to its much greater spatial resolution, allows ice conditions to be resolved within the passive microwave field of view. For example, comparison of a time series of SMMR data with manually-interpreted Landsat imagery helps to set some bounds on the performance of a standard passive-microwave algorithm during melt-onset and melt (*Steffen and Maslanik*, 1988). Also, since thin ice types could be mapped using the Landsat data, it was possible to demonstrate the relationships between microwave polarization ratio and ice thickness. In turn, these relationships can be used to help develop thin-ice algorithms applicable to the microwave data.

In a similar approach combining error assessment with application toward new algorithms, *Maslanik* (1991) calculated the effects of surface winds and atmospheric water on retrievals of ice concentration and ice type from passive microwave data. Wind, water vapor, and cloud liquid water cause overestimates in ice concentration and more substantial underestimates in multiyear ice percentage. Advantages and limitations of the operational gradient-ratio weather filtering methods were described, and relationships among polarization ratio and gradient ratio were used to devise an alternative scheme to adjust for weather effects in the marginal ice zone. Other efforts are underway (see also Key, this report, p. 11) to combine model output and a variety of data types through artificial intelligence methods to improve algorithm performance.

Conclusion

Our focus has been to use passive microwave data to study climate processes operating on interannual and shorter time scales, with particular emphasis on processes within the interior ice pack, a region sparse in surface observations. As part of this effort, we continue to seek ways to better understand the limitations of the remotely-sensed data, to improve existing algorithms, and to devise methods to extract additional information from the imagery. For the study of large and rapid changes in ice concentration in particular, the microwave data are quite valuable since the observed changes are substantially higher than the inaccuracies in the algorithms, especially when other information types and interpretation methods are combined to help remove some of the ambiguities in the microwave clear that the brightness temperatures them-

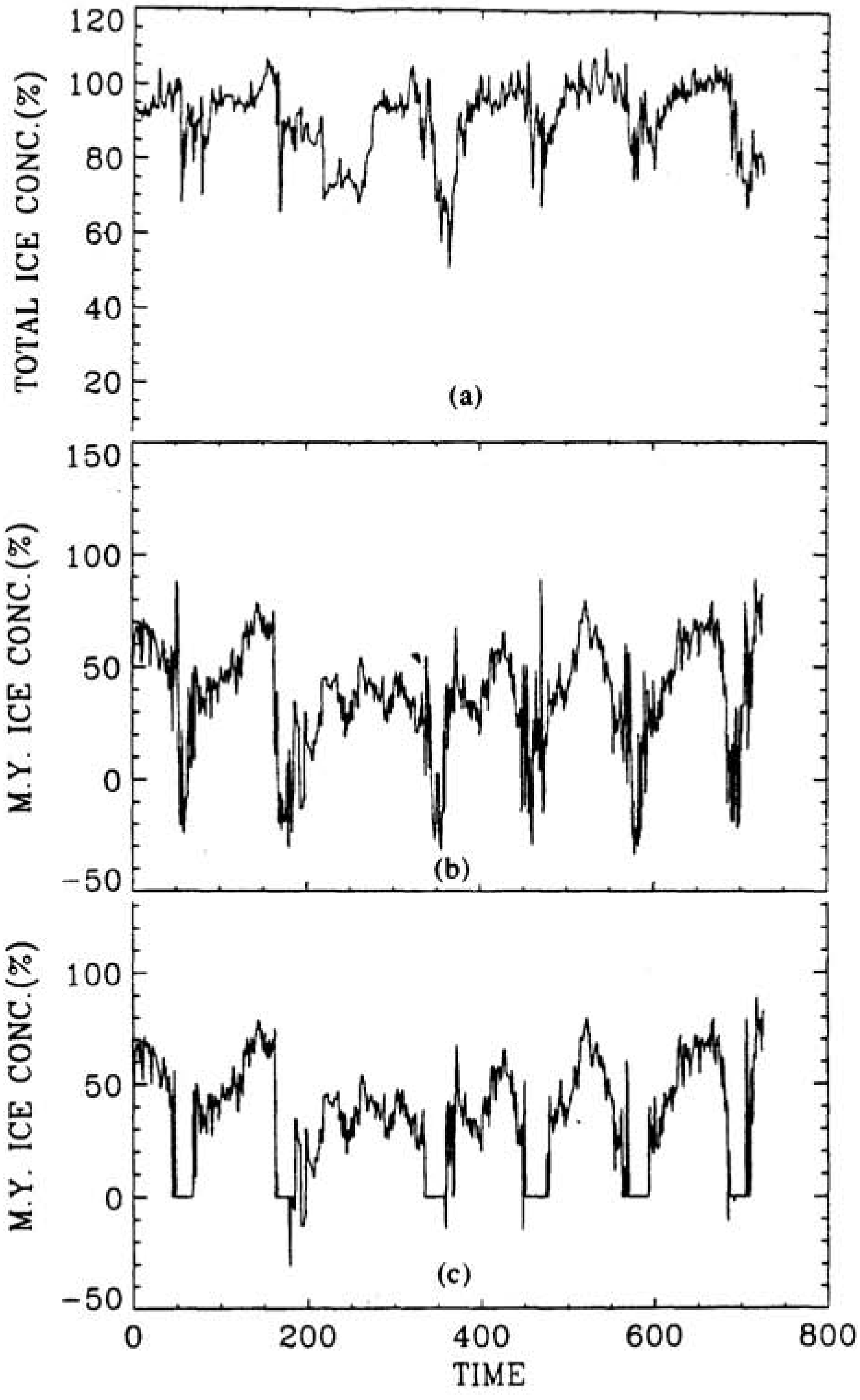

Figure 1. Total ice concentration (a), unfiltered multiyear ice concentration (b), and filtered multiyear ice concentration (c) as calculated using the expert-system implementation of the NASA Team Algorithm. The filtered multiyear ice concentration (e.g., concentrations coded to 0%) in (c) correspond to observations when either the buoy temperature or the modeled ice surface temperature for thick ice duirng that period was >=273 K.

selves, in addition to the derived ice concentrations, should be carefully studied. We expect to continue to combine satellite data with physical models to resolve some of the cause-and-effect issues in the Arctic atmosphere-ice-ocean system, and will further investigate methods of combining physical models with empirical algorithms to minimize uncertainties in both model performance and retrieval of ice conditions from satellite imagery.

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Application of Passive Microwave Satellite Data in Arctic Climate Research

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Introduction

The role of high latitudes in the global climate system is still poorly known and inadequately modeled, yet the polar regions are predicted to be highly sensitive to the projected warming effects of increasing greenhouse gas concentrations (*Barry, 1985*). Important climate parameters at high latitudes are estimates of the seasonal changes of open water in the Arctic pack ice to an accuracy better than one percent, surface energy fluxes of latent and sensible heat, cloud amount and cloud type, boundary layer height and strength of the winter inversion. General circulation model simulations of $C0_2$ doubling generally predict the warming to be amplified in the polar regions. This is mainly due to the well known temperature - albedo feedback and the fact that radiative warming is confined to a shallow surface inversion layer (*Mitchell*, 1989). In both mechanisms sea ice provides a positive climate feedback. If model predictions are correct, the effect of a CO_2-induced warming of the global climate system might be detectable in long-term changes of sea ice extent. Thus, long-term monitoring of sea ice variability is of prime interest for studies of climate trends and low frequency variations. Based on the analysis of nine years of Nimbus 7 Scanning Multichannel Microwave Radiometer (SMMR) observations, *Gloersen and Campbell* (1988) reported that no significant trends are present in the global ice area or in the annual ice extents for either polar pack, although open water areas within the pack ice had increased. The absence of trends was confirmed by *Parkinson and Cavalieri* (1989) in an analysis of SMMR-derived sea ice cover for the entire Arctic Basin. However, they showed that the ice extent exhibited both upward trends (e.g., Baffin Bay/Davis Strait) and downward trends (e.g., Kara and Barents seas). Data on sea ice variability should further improve our ability to quantify atmosphere-sea ice interactions and establish physically sound parametrization for climate models.

In light of the fact that even small changes in sea ice extent might have a significant influence on energy fluxes between ocean and atmosphere (*Maykut*, 1978), it is important to determine the accuracy with which sea ice parameters such as ice concentration (ice free areas) and ice extent can be monitored with today's satellite technology. Passive microwave data collected by satellites have been used to monitor sea ice in polar regions since 1973. Using the multiple frequencies provided by the SMMR, 1978-1987, algorithms with the ability to derive sea ice concentrations have been developed (*Cavalieri et al.*, 1984; *Comiso*, 1986; *Gloersen and Cavalieri*, 1986). On June 19, 1987, the Defense Meteorological Satellite Program (DMSP) launched the Special Sensor Microwave Imager (SSM/I). The SSM/I is a passive microwave radiometer which provides near real-time data for operational use and for specific research areas (e.g., sea ice) (Weaver *et al.*, 1987).

Accuracy of Ice Concentration Retrieval

This section summarizes the validation of an algorithm for the determination of sea ice parameters which has been developed by NASA scientists (referred to as the NASA Team Algorithm) for the DMSP-SSM/I data stream (*Steffen and Schweiger, 1991*). The general question to be addressed is "with what accuracy (relative to these other observations) can we determine total sea ice concentration". Another concern is how the accuracy with which these parameters are determined varies between different regions (e.g., marginal ice zones such as the Bering Sea, or Arctic Ocean areas such as the Beaufort Sea), and over different seasons. Further, the sensitivity of passive microwave sea ice concentration algorithms to the selection of locally and seasonally adjusted algorithm parameters is discussed.

Landsat MSS satellite images provide a powerful tool to estimate ice concentration in cloud-free areas with sufficient daylight (solar elevation > 5°). Landsat ice concentrations can be derived within an accuracy of 2 to 4%, considering sensor noise, geolocation and errors due to spectrally or spatially unresolved surface features (*Steffen and Schweiger, 1990*). Black nilas and shuga, ice types of less than 0.05m in thickness, cannot be resolved with Landsat MSS sensors. However, this shortcoming is negligible, considering the time difference of Landsat and DMSP satellite orbits over the same area (up to 8 hours) and the fact that black nilas and shuga grow within a few hours during the freeze-up period. For validation of the DMSP SSM/I ice algorithm, 28 cloud-free Landsat scenes were selected, providing a variety of ice concentrations and ice types from the Beaufort, Bering, Greenland, Weddell, and Amundsen seas.

Mapping of sea ice parameters using passive microwave data is possible owing to the large difference in emissivity between calm water and sea ice. In addition, the differences in emissivity of first-year versus old ice (sea ice that has survived at least one melt season) at different microwave frequencies provide a means of separating ice types. The capabilities of passive microwave data in sea ice research have been discussed in a number of articles (*Svendsen et al.*, 1983; *Comiso*, 1986; *Cavalieri et al.*, 1984; *Gloersen and Cavalieri*, 1986; *Steffen and Maslanik*, 1988). The derivation of ice concentrations from the SSM/I data was carried out using the algorithm described by *Cavalieri et al.* (1984), with the addition of the weather filter as discussed by *Gloersen and Cavalieri* (1986). Two different tie point sets were used for this comparison - both global and local tie points. For global tie points one assumes that during winter the only significant variability in signatures arises from surface temperature variations, most of which can be removed by using ratios of brightness temperatures. With that in mind, these tie points were selected for regions which are thought to contain just one surface type. This was done separately for the Arctic and the Antarctic. Local tie points were derived according to the above described method, for a particular region and season.

Ice concentrations during fall can be derived from passive microwave data with a mean difference of 0.3% (compared to Landsat ice concentrations) and a standard deviation of ±3.1%, using the NASA Team Algorithm with local tie points. With global tie points a mean difference of 0.1% and a standard deviation of ±6.2% is found. During winter, a comparable performance of the NASA Team Algorithm is expected, because of similar ice conditions.

In spring, the overall accuracy of the NASA Team Algorithm is lower compared with fall, with a mean difference of the order of -2.4% and a standard deviation of the difference of ±4.8% for local tie points. For global tie points the mean difference is -5.6% with a standard deviation of ±5.9%. In areas with higher amounts of nilas and young ice, we found that the SSM/I ice concentration algorithm underestimates ice concentrations by as much as -9% (global tie point), or -4% (local tie point) with standard deviation of ±6.1% for global as well as local tie points. Maximum differences between SSM/I and Landsat ice concentrations of over -20% for individual pixels were observed in two separate Landsat-SSM/I comparisons.

The derivation of an ice concentration error estimate for the NASA Team Algorithm during summer is complicated by a number of factors. Due to the usually lower ice concentrations, wind and ocean currents can cause rapid changes in ice conditions over relatively short periods of time. Time difference in the overpasses between the DMSP and the Landsat satellite can therefore cause substantial differences. Further, ice concentration from Landsat data may be inaccurate due to the presence of melt ponds and rotten ice so that the determination of thresholds is difficult. Differences between SSM/I and Landsat ice concentrations range between -24% and 46%. These large errors, though expected due to the problems of surface melt during summer, might also reflect inaccuracies in the reference (Landsat) data set and have to be interpreted with caution.

The performance of the NASA Team Algorithm compared with Landsat-derived values, for all case studies in spring and fall, gives a correlation of 0.968 using global tie points (Figures 1 and 2). The NASA Team Algorithm underestimates ice concentration in areas of close pack ice, and overestimates ice concentration in areas of open pack ice. Using local tie points for the same case studies, the correlation coefficient increases to 0.982, and the regression line shows the same characteristic as described for the global tie points (Figures 1 and 2).

It appears that seasonal and regional adjusted tie points (local tie points) will improve the overall performance of the SSM/I sea ice concentration algorithm. Our work suggests that where the ice has a larger variation of internal characteristics (e.g., salinity), global tie points will cause a standard deviation of about ±7% for spring and fall ice concentration. Use of local tie points lowered the standard deviation to ±5% for the same cases studied. In the south polar regions, where the ice cover is essentially first-year, the global tie points perform reasonably well.

In view of a possible climate change, the polar regions will be a focal point because of their sensitivity and positive feedback to small changes. Satellite passive microwave data with their all-weather and all-season capabilities will play an essential role in long-term monitoring of the sea ice cover in both hemispheres. The future will show whether the accuracy of SMMR- and SSM/I-derived ice concentrations will be adequate to detect possible changes. The accuracy of the NASA Team Algorithm could be improved further when used in combination with algorithms for young ice type classification, or in combination with other multi-spectral or multi-sensor data sets.

Passive Microwave Data for Young Ice Typing

Microwave scattering of sea ice is due to the inhomogeneity of density and structure variations, whereas microwave absorption is mainly determined by the presence of liquid inclusions (brine volume). The relationship between the vertically-polarized brightness temperatures and sea-ice properties such as brine volume or porosity are well known (*Mätzler et al.*, 1984), whereas the horizontally-polarized brightness temperature is sensitive to surface roughness. In a previous study it was found that the polarization ratio at 18 and 37 GHz increases with decreasing ice thickness (*Steffen and Maslanik, 1988*). The polarization ratio is defined as:

$$PR_{fq} = (T_B(V,fq) - T_B(H,fq)) / (T_B(V,fq) + T_B(H,fq))$$

where PR_{fq} is the polarization ratio at frequency fq, $T_B(V,fq)$ and $T_B(H,fq)$ is an observed brightness temperature at frequency fq and vertical or horizontal polarization. In that study, ice types such as white ice (WI: > 0.3 m thickness), grey and grey-white ice (GI: 0.1 - 0.3 m thickness), nilas (NI: < 0.1 m thickness) and open water (OW) were determined visually from Landsat multispectral scanner band 7 (near-infrared imagery, 800-1100 nm) for the North Water area, and plotted versus the PR of 18 and 37 GHz. The comparison was made for 260 SMMR grid cells (25 x 25 km) of the North Water pack ice in spring 1981 for which 100% of the above specified ice types occurred. The decrease of PR with increasing ice thickness could be the result of the reduction in brine volume when the ice becomes thicker and colder, in other words, the sensitivity of the vertically polarized bright-

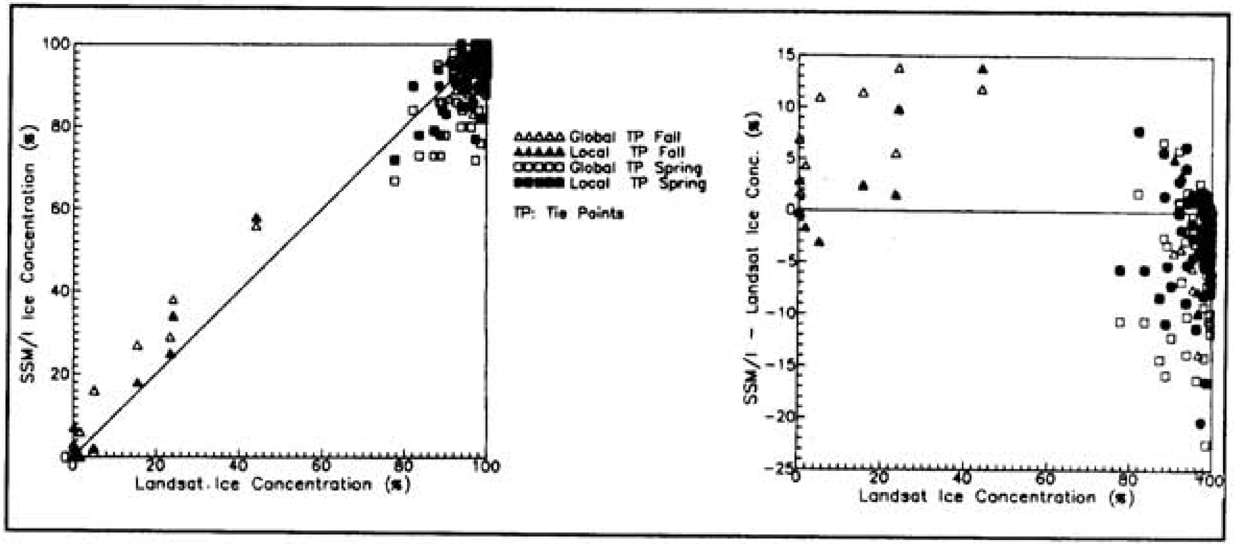

Figure 1. Comparison of ice concentration (50 km grid) between NASA Team Algorithm using local and global tie points versus Landsat values for the Beaufort, Chukchi, Weddell and Greenland seas, spring and fall conditions.

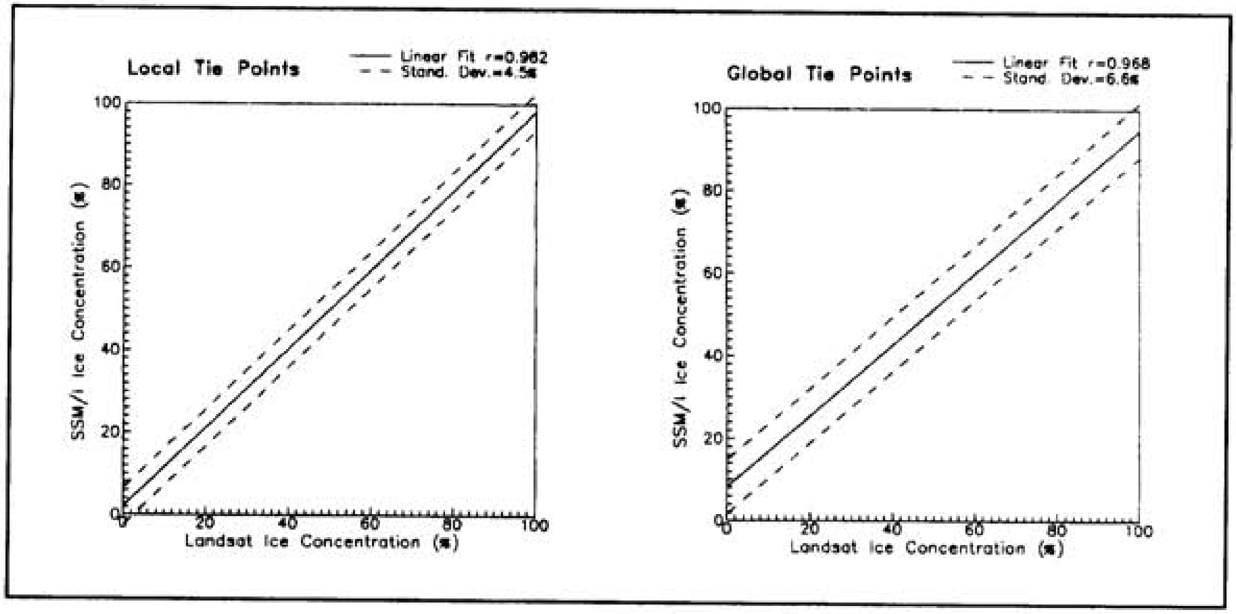

Figure 2. Linear regression lines for all case studies in spring and fall (Fig. 1) for local (left) and global (right) tie points. The correlation coefficient for local tie points is 0.982, and 0.968 for global tie points. The dashed lines depict one standard deviation, ±4.5% for local tie points, and ±6.6% for global tie points respectively.

ness temperature to the decrease in salinity. Large variabilities of horizontal polarization are caused by surface roughness on a small scale (*Mätzler et al., 1984*). However, by averaging over a large area (one SMMR pixel), the scatter may be smeared out, and the average value resulting from the thin snow cover and the young ice in the North Water may not be influenced by the disturbing effect.

The standard deviations of open water, nilas and grey ice do not overlap for 18 GHz, indicating that a classification of these ice types based on satellite-derived PR may be possible over fully consolidated ice (Figure 3). For grey ice and white ice the standard deviations at the same frequency show a small overlap. For 37 GHz only, water and nilas can be classified with the PR method with a certain degree of confidence. White ice, grey ice, and, to some degree, also nilas show a considerable overlap of the PR standard deviations. The larger standard deviation at 37 GHz compared to 18 GHz could be explained by the larger sensitivity of 37 GHz to water vapor; microwave absorption and zenith opacity are three times more sensitive to water vapor at 37 GHz compared to 18 GHz . The standard deviations of open water show a broad range that can be explained by the presence of small ice floes not resolved in the Landsat imagery and by the brightness temperature change due to wind-induced spray and foam on the ocean surface.

Similar PR values for the above mentioned ice types were reported by *Cavalieri et al.* (*1986*) for aircraft measurements in the Bering Sea, and by *Grenfell* (*1986*) for ground-based measurements from the Greenland Sea. Radiometric observations of sea ice growth in a tank also showed a decrease of PR with increasing ice thickness, however, the PR reached a limiting value when ice thickness was 20 to 25 mm for air temperatures between -2° to -15° C (*Grenfell and Comiso, 1986*). Their study also showed significant changes in PR even though the ice thickness was nearly the same while the air temperature changed by several degrees. For the North Water, sea ice brine volume is assumed to be higher than during the Grenfell and Comiso tank experiment due to the lower air temperatures of -20° to -30° C resulting in a larger difference between horizontally- and vertically-polarized brightness temperatures.

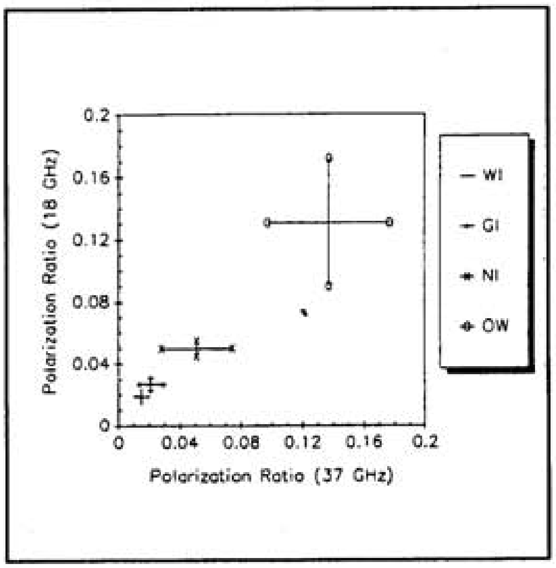

Figure 3. Passive microwave SMMR polarization ratios ± standard deviation at 18 and 37 GHz derived by intercomparison with Landsat imagery for white ice (WI), grey ice/grey-white ice (GI), nilas (NI) and open water (OW).

Based on the relation of increasing polarization ratio with decreasing ice thickness as verified with the Landsat comparison for the North Water area, a threshold technique was applied to classify the different ice types. For the ice typing, the following PR values were used for 18 and 37 GHz (*Steffen, 1991*):

37 GHz:	18 GHz:
0.086 < OW	0.071 < OW
0.085 > NI > 0.031	0.070 > NI > 0.041
0.030> GI > 0.019	0.040 > GI > 0.023
0.018 > WI	0.022 > WI

The 18 GHz PR is less effected by water vapor (see smaller standard deviation in Figure 3), and therefore, is preferable for applications over polynyas with large amounts of low level clouds due to extensive latent energy flux

density. However, the SMMR pixel at 18 GHz has a field of view of 60x60 km, which represents only 50% of the actual power received by the radiometer. The 37 GHz frequency has a field of view of approximately 25x25 km which seems more realistic for young ice classification in polynyas. For winter pack ice conditions with a small fraction of open water and thin ice, this method may give erroneous results because the SMMR pixel of 25 km in dimension is certainly larger than the thin ice areas. This is the major shortcoming of this proposed PR ice type classification method and limits its application to large homogeneous ice areas consisting of a single ice type which are often found in large polynyas such as the North Water.

Passive Microwave Data for Heat Flux Retrieval

The potential of passive microwave-derived sea ice information for the calculation of heat fluxes at the Arctic ocean surface was investigated. The sensitivity of individual surface energy balance terms to the information content and the inherent error in the passive microwave-derived sea ice parameters was tested using a simple energy balance model of the ice covered ocean surface. The model follows Maykut (*1978*) with a modification to allow for variable lead sizes as discussed by (*Steffen et al., 1990*). Ice thickness distributions from dynamic ice modelling experiments (*Maykut, 1982*), as well as climatological data on radiative components, were utilized to compute turbulent fluxes over sea ice. Calculations were made using the full (Maykut-type model) thickness distribution in five categories, a two-category thickness distribution (ice/open water) optimized for passive microwave data, and a three-category thickness distribution (thick ice/thin-ice/open-water) using a passive microwave algorithm assuming a limited thickness (< 0.8 m) of the first-year ice category. Some of the preliminary results are summarized below.

Marginal Ice Zone

In the marginal ice zone, where thin ice types dominate, information on the relative abundance of these ice types is necessary to compute turbulent fluxes with any reasonable accuracy. Current passive microwave algorithms are not capable of producing this type of information. Even though individual studies (*Steffen, 1991*) have shown that the different emissivity of thin ice indicates a potential for the retrieval, this capability is limited to situations when the extent of thin ice types is large enough to cover an entire footprint. Further work, through a combination of different sensors, e.g., AVHRR, ice surface temperatures or inclusion of coupled dynamic/thermodynamic ice models, might improve this situation.

Central Pack Ice

In the central pack, the use of ice concentrations in the calculation of the turbulent part of the energy balance faces a different set of problems. If one assumes that ice concentrations may be retrieved with 100 % accuracy by a particular passive microwave-based sea ice concentration algorithm, then the potential error due to poor thickness resolution (two-category algorithm, open water/ice) is of the same order of magnitude as the variability that can be expected to be observed (Figure 4). This fact eliminates the capability to monitor any changes in the surface energy balance due to changes in ice concentrations over time. The inclusion of passive microwave-observed ice concentrations will not significantly improve estimates of surface energy balance calculated solely from other data. While a hypothetical three-category thickness algorithm (0.0-0.1m, 0.1-0.8 m, > 0.8 m) would significantly reduce the above discussed problems (compare Figure 5 to Figure 4), the following question needs to be answered:

In what way do variations in the observed passive microwave signal and derived geophysical parameters (ice types: open water, *first-year ice, multi-year ice) relate to energy balance calculations (turbulent component)?*

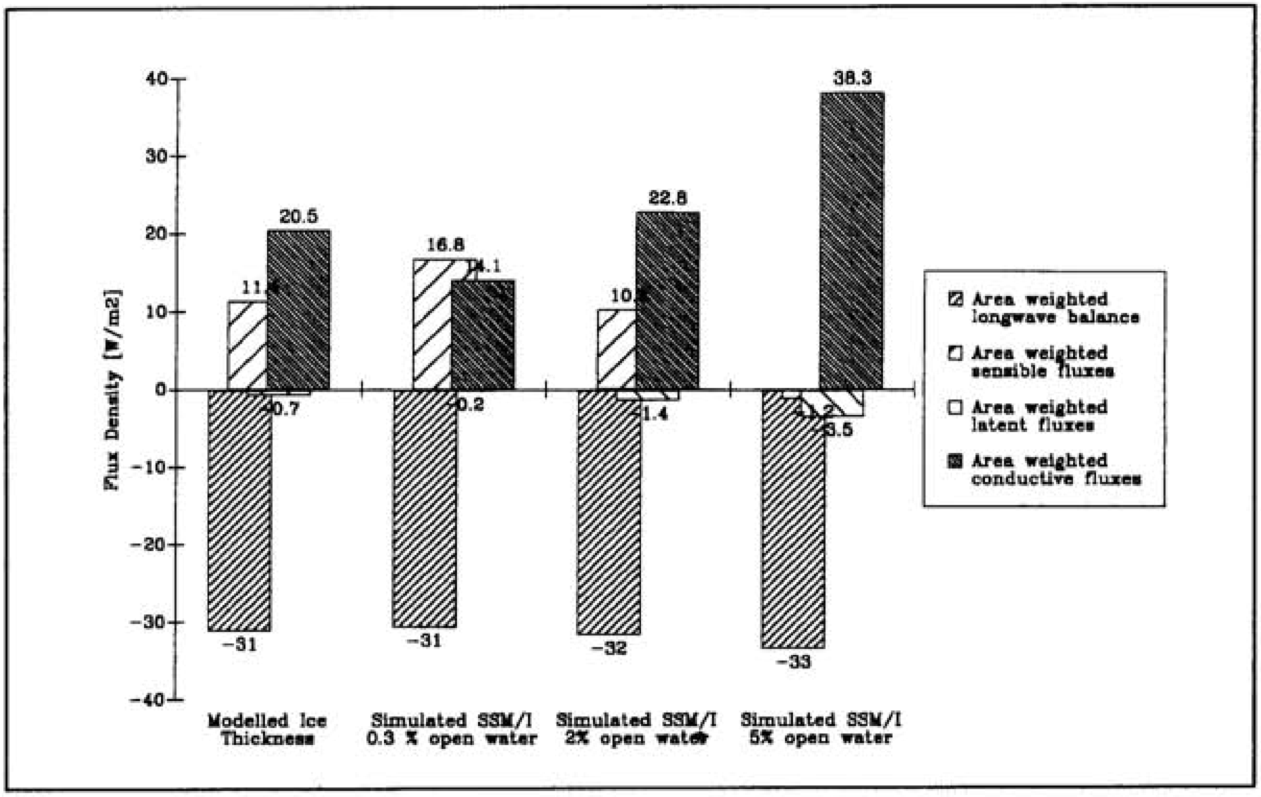

Figure 4. Central Arctic energy balance in January calculated from a number of different ice thickness distribution categories.

Category 1 (modelled ice thickness) represents the energy balance as calculated for the full thickness distribution derived from dynamic/thermodynamic model calculations.

Category 2 (simulated SSM/I 0.3 %) represents the energy balance calculated based on a simulated SSM/I algorithm. SSM/I ice concentrations were simulated by summing ice thicknesses > 0.05 m in the modelled ice thickness distribution.

Category 3 represents the energy balance in January when 2 % open water would be present, corresponding to the observable natural variability.

Category 4 assumes 5 % open water which would have to be considered an extreme case.

Note that the difference between category 1 and 2 is caused by the reduced resolution in ice thickness estimate as derived from SSM/I data. This uncertainty is of the same order of magnitude as the expected variability.

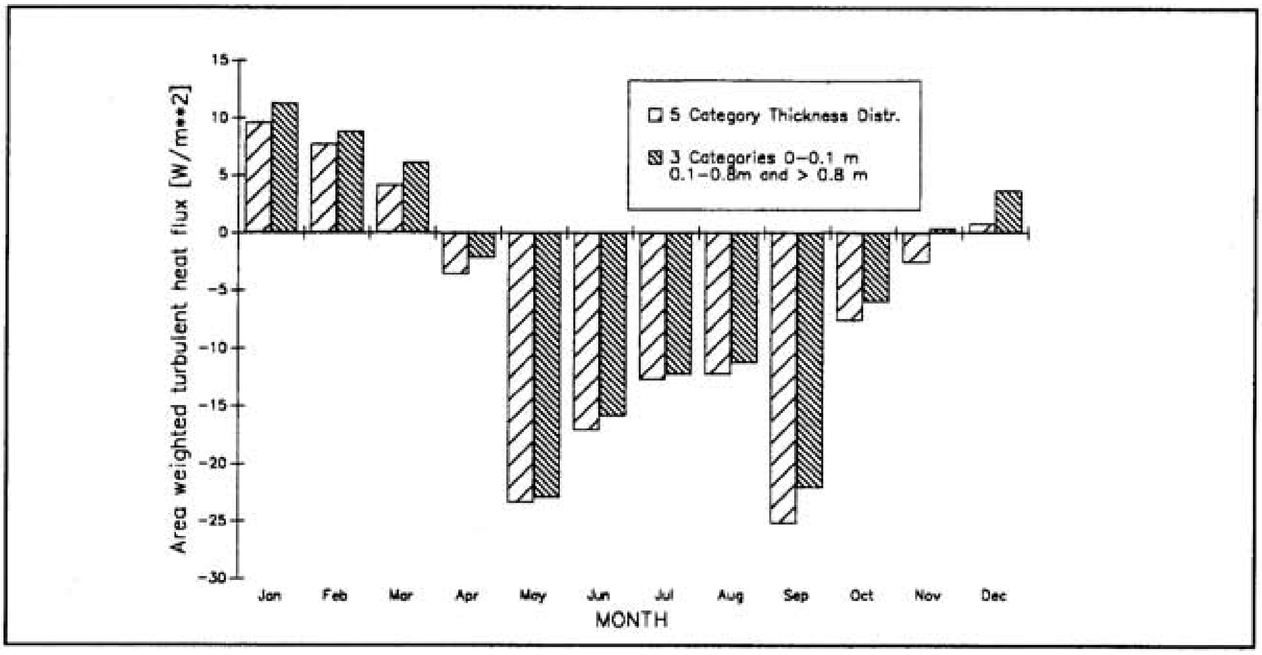

Figure 5. Turbulent heat fluxes [Wm^{-2}] calculated for a 5 category (0-0.1, 0.2, 0.4, 0.8, > 0.8m) and 3 category (0-0.1, 0.8, >0.8 m) thickness distribution.

If one assumes that first year ice grows to a certain thickness (up to 0.8 m), then flux calculations would be relatively straight forward assuming a linear temperature gradient in the ice. Fluxes over the thick multi-year ice could be estimated using a multi-level thermodynamic model (*e.g., Semtner, 1976*). Certain assumptions would also have to be made regarding how to model the characteristics of the ice surface due to ice movements. We are considering alternatives on how one might model ice floes that are moving through regions of differing energy balance conditions (e.g., ice flows from the marginal pack through the central Arctic or vice versa).

Unfortunately, the assumption of FYI representing a category of particular ice thickness is not a very good one, since thin ice is constantly undergoing dynamic deformation. Thermodynamic profiles of deformed FYI are most likely similar to those of MYI, and can therefore not be approximated using the linear gradient model (unpublished data, Resolute Bay, K. Steffen). Due to this fact, a passive microwave-based algorithm would have to produce information on open water fraction, undeformed FYI and deformed ice. There is some indication that deformed FYI signatures are similar to those of MYI because of brine drainage and greater amounts of snow, but evidence for this fact is sketchy and can hardly be accepted in a general sense.

An alternative route in deriving a climatology of the Arctic surface energy balance would be the use of thermodynamic/dynamic models. Multi-layered versions of these models provide information on the ice thickness distribution which would be more suitable in calculating turbulent heat exchange at the ice surface than in coarse thickness resolution of the passive microwave data.

If ice thickness distributions can be modelled, the use of passive microwave information in the calculation of the Arctic surface energy balance assumes a different role. This role would be the validation and accuracy assessment of the modelled ice concentrations. If modelled ice concentrations match passive microwave-derived concentrations, the argument may be made that the ice thickness redistribution function reflects the physical processes involved in converting the various ice thicknesses is also correct. An important step in the compilation of an ice thickness climatology would therefore be the cross-validation of modelled and passive microwave-derived ice concentration. This comparison would further provide some limits on the errors that can be expected in the calculation of the surface energy balance based on modelled ice thickness distributions.

In the previous discussion we made the assumption that ice concentrations can be retrieved with absolute accuracy by a passive microwave-based algorithm. This of course is not so. We have found in previous studies that the error in ice concentrations lies in the range of ±3 % to ±5% depending on the season (*Steffen and Schweiger, 1991*). The selection of appropriate tie points for particular areas and times of the year might distribute the error evenly about the mean, so that for longer term averages, the assumption of an accurate open water fraction might not be such a bad one.

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Passive Microwave Bibliography

Introduction

This passive microwave bibliography is a compilation of references on passive microwave theory, research, and applications, 1988-1991. It updates the bibliography published in *Glaciological Data, GD*-19, 1987. The bibliography includes both subject and author listings. Subject categories include:

This bibliography has been compiled from a variety of sources, particularly the online data bases listed below.

COLD (Bibliography of Cold Regions Science and Technology)

Aerospace Data Base (International Aerospace Abstracts; Scientific and Technical Aerospace Reports)

NTIS (U.S. National Technical Information Service)

Compendex (Engineering Index)

Meteorological and Geoastrophysical Abstracts

CITATION Data Base (WDC/NSIDC).

Because we do not have all of the original material in hand, we cannot be certain of the completeness of each citation. However, every effort has been made to ensure accuracy.

We would appreciate your comments on the bibliography — on references we have not included, sources not searched, or subject areas not adequately covered. We plan to keep this bibliography up-to-date and your suggestions are welcome.

Ann M. Brennan
Compiler

SUBJECT LISTING

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