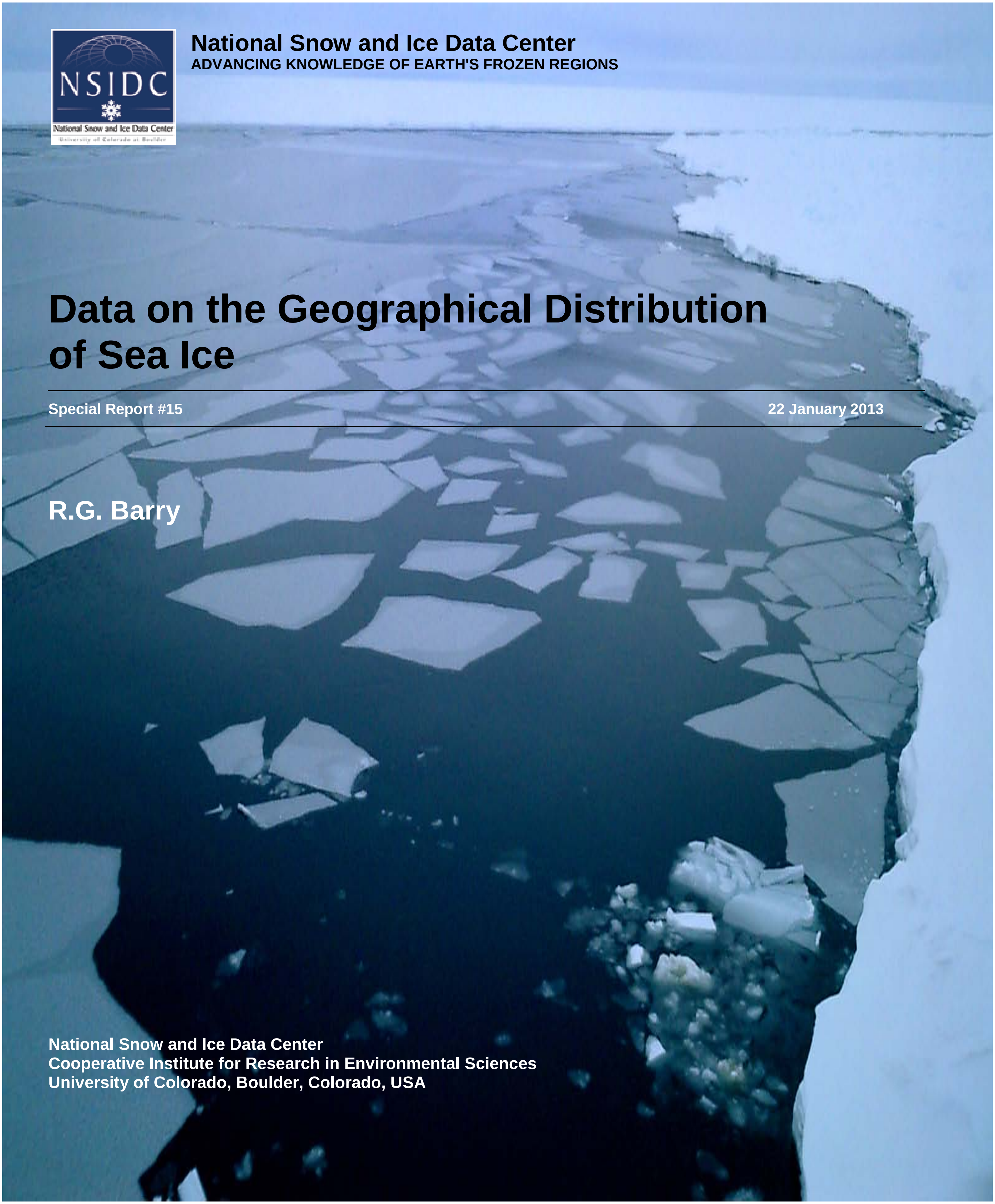

National Snow and Ice Data Center
ADVANCING KNOWLEDGE OF EARTH'S FROZEN REGIONS

Data on the Geographical Distribution of Sea Ice

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Contents

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Foreward

Sea ice is changing quickly. One can no longer look back in time to understand the probability of a particular sea ice behavior anymore, and sea ice climatologies are no longer the aid to forecasters that they once were. In addition, the mean and variance of parameters like sea ice extent and concentration are no longer considered stationary.

To understand these changes in context, it is important to have early records of ice cover. Review papers that gather these references together are valuable, especially because few exist. This work falls in that category. The sections titled The Historical Database, Ice Indices, and Ice Atlases are particularly useful, as is the discussion of the reliability and representativeness of historical sources. Indeed, the reference list alone is a valuable bibliography of unique sea ice data sources.

This report was distributed by NSIDC in 2000 as part of the EWG Sea Ice Atlas on CD-ROM data set (http://nsidc.org/data/g01962.html). Some of the material was first published in 1986 in The Geophysics of Sea Ice (Barry, R. 1986. The Sea Ice Database. In *The Geophysics of Sea Ice*, ed. N. Untersteiner, 1099-1134. New York: Plenum Press.) It is being re-published as an NSIDC Special Report in order to broaden its distribution. It has not been updated since 2000, so the material on analysis methods at operational ice centers and data centers is quite dated. However, the information is valuable as it documents the methodology and data sources used to assess ice conditions in the 1990s.

- *Florence Fetterer, NSIDC, January 2013*

Introduction

Sailing vessels and shore stations have long recorded sea ice conditions in many parts of the world oceans and a more complete global picture has become available via aerial surveillance and satellite remote sensing over the last several decades. The types of measurements that are made vary considerable in terms of the parameters recorded, their frequency, resolution, reliability, and geographical coverage. Also, whereas standard terminology, practices for ice observations, and codes for their reporting have been documented (e.g. U.S. Naval Oceanographic Office, 1956: Heap, 1972) and the Sea Ice Grid (SIGRID) format for display of ice information on charts (Thompson, 1981) has been widely adopted, international standards for data archiving have only recently been formulated (WDC-A for Glaciology 1979; Thompson, 1981; Krutskikh, 1984). As a result, the state of sea ice data bases remains primitive by comparison with those for meteorological information.

The Historical Database

There are few long-term historical records of sea-ice conditions. The longest and best-known is that compiled by Koch (1945) from an historical survey of Iceland's climate by P. Thoroddsen in 1917. This describes the incidence of East Greenland ice on the coasts of Iceland since AD 860. Lamb (1977, p. 583) tabulates the yearly record of weeks/year with drift ice at the coast, after Koch with some additions, from AD 1600 to 1975; the annual series is believed to be complete from 1780. A related record of the extent of the Storis drift along the west coast of Greenland exists from 1821 (Speerschneider, 1931; Koch, 1945; Lamb, 1977, p. 582). These types of record are shown in Figure 1 which illustrates the different ranges of variability according to the parameter selected. Recently, new attempts have been made to cross-check the reliability and completeness of the early Icelandic sources used by Koch and others. Vilmundarson (1972) illustrates discrepancies in 17th century sources concerning the ice extent in particular years and notes the potential value of official letters on conditions in Iceland, especially for the 18th century. Ogilvie (1984;1992) has identified further sources showing that sea ice was common off the north coast in the 1590's whereas the Koch graph suggests little or none. For the waters around Denmark, Speerschneider (1915) has drawn attention to the problems of early records: unreliable ancient reports of ice conditions, the defects of old maps, the changing designations used to refer to segments of Danish coastal waters, and the misidentification of the year in which as severe winter season occurred. The Icelandic record appears to be a useful measure of ice in the northern North Atlantic, but it provides only a regional indication of northwesterly airflow over the Greenland Sea (Kelly *et al*., 1987).

Other long series are available for the Baltic Sea and adjacent waters. Two major ones provide an annual winter maximum extent of ice from 1720 to 1956 and the spring breakup, indicated by the final opening of the port of Riga, annually from 1710 with less continuous data from 1530. Tabulations of these records, compiled by Speerschneider (1915, 1927), and Betin and Preobazhensky (1959), are provided by Lamb (1977, pp.586-9). Jurva (1952) has analyzed changes in ice area in the Baltic for 1830-1951 and this is updated by Koslowski and Loewe (1993; 1994) for 1879-1992. They demonstrate that Baltic ice severity is related to the atmospheric North Atlantic Oscillation (NAO) index. Mild ice years correlate with positive NAO representing strong westerlies over the North Atlantic.

The problems of historical data are illustrated by the work of Hunt and Naske (1979) for the Alaskan coasts. They used the log reports of whaling and trading ships operating in the Bering, Chukchi and Beaufort Seas from the late nineteenth century. Charts of the average ice edge are shown for the summer months for 1860-79, 1800-1919, 1920-70, but no details are given as to the procedures used or number of data points available. These charts show lighter ice conditions after 1940 and a tabulation of ice data from 1900 at Point Barrow by Swithinbank (1960) gives the same result. This is in apparent conflict with the ice retreat estimated from climatic records for Barrow since 1926 (Barry, 1979), and it is unclear how far this represents differences in definition of the ice edge seen from small whaling ships and from modern vessels and aircraft/satellite imagery, or whether there are ice-climate relationships that have been inadequately interpreted using only recent data. An analysis of inferred ice conditions from weather records at Barrow for 1882, 1883, 1902, 1911 and 1916, compared with the ice conditions reprted by Hunt and Naske (1979), indicates agreement in 1902 and 1911 (light ice), some disagreement in 1882 and 1903, and insufficient data for comparison in the other two years.

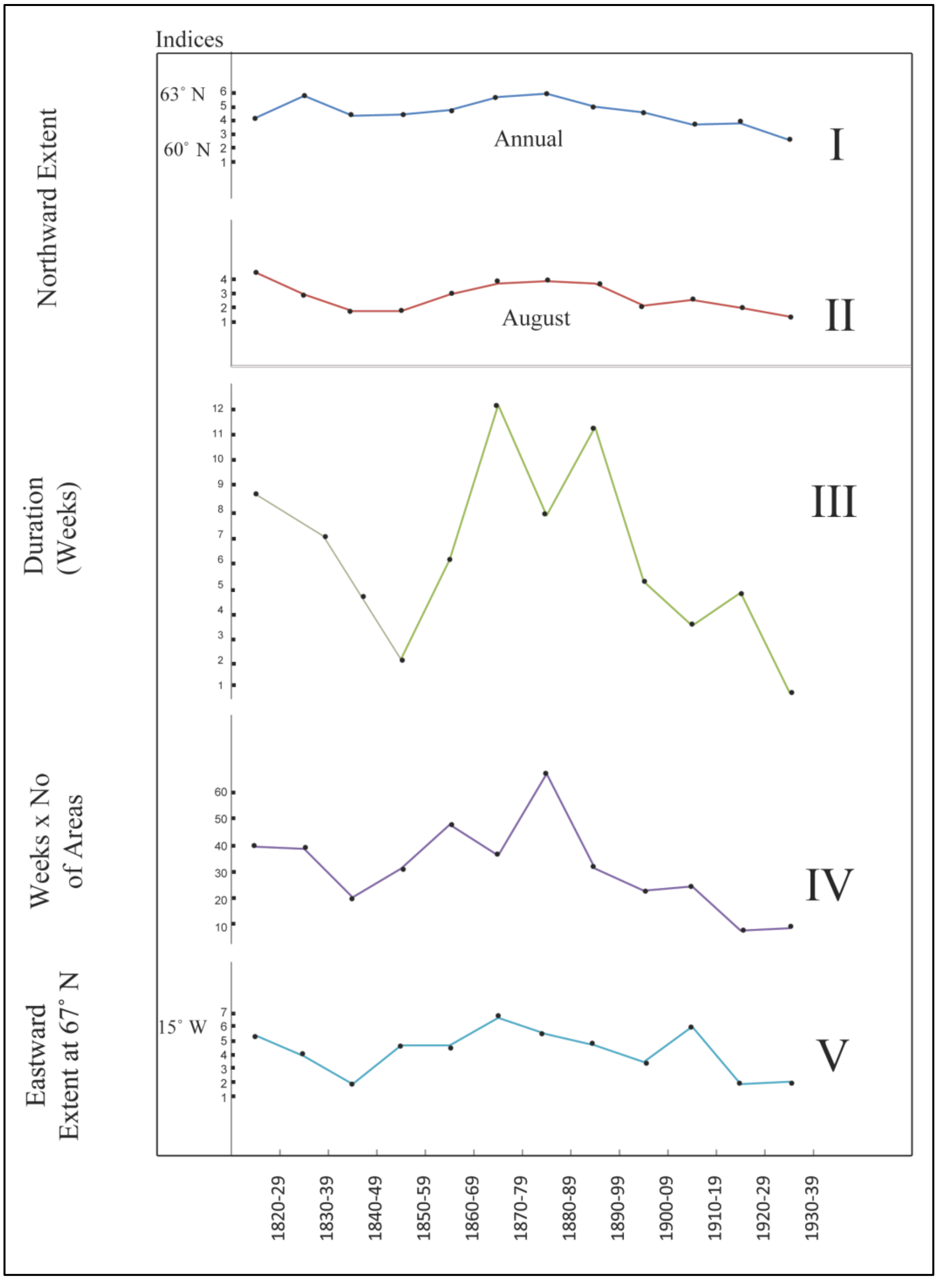

Figure 1. Examples of long records of ice conditions around Greenland and Iceland, I = West Greenland annual ice (after Speerschneider), II = West Greenland August ice (after Koch), III = weeks with East Greenland ice off Iceland (after Thoroddsen), IV = weeks x

The most complete ocean-wide historical information is that available for the Arctic in the monthly ice charts for April to August or September published by the Danish Meteorological Institute (1901-39 and 1946-50). The data coverage is moderately good in the North Atlantic sector where charts are available from 1877 (Ryder, 1896). For the Barents Sea, Norwegian records are available from 1853-1900s; Vinje (1998) is developing an ice index for the sector 20º-45ºE. There is also discontinuous information for April for the intervals 1580-1600s and some years in the 12th century. There are also extensive archives of 18-19th century ice information for the Russian Arctic at the Arctic and Antarctic Research Institute in St. Petersburg (Abramov and Smolianitksi, 1997). This is discussed further below. For more recent years, aircraft reconnaissance and satellite data provide a fuller picture of both polar regions. Early

Soviet work with aircraft in the Arctic is reported by Armstrong (1950). Regular Soviet reconnaissance flights began in 1924 with extensive routine summer operations from 1933 (250 hours/year, increasing to over 500/year from 1950, and a maximum of 900/year from 1970 to the early 1990s). Regular United States aerial reconnaissance flights in the Arctic date from 1952. Results from these operations are presented in a series of reports published by the U.S. Navy Hydrographic Office (1954) and the U.S. Naval Oceanographic Office (1956;1962-74). A summary of microfilm records of Danish reconnaissance flights in the Greenland area and U.S. satellite data for the Arctic and Antarctic from 1972-1976 is given by Mitchell (1976, 1977). Aerial ice reconnaissance data for the Canadian Arctic Archipelago are also contained in atlases for the summer seasons of 1961-78 (Lindsay, 1975, 1977, 1982). These give approximately six to ten charts for each year showing the existing fractional concentration of three ice types, and ice forms such as ridging. A complementary analysis for the same area for 1900-1958 is provided in an earlier atlas by Swithinbank (1960). There is much more information available in Swithinbank's study for the 1950s than for the preceding 50 years, however. The atlas also contains maps of the frequency of three ice concentration classes at 324 locations for each season in the Canadian arctic islands and adjacent seas. Swithinbank uses both ship and shore observations and some U.S. Navy Hydrographic Office aerial reconnaissance information. The categories of ice concentration that are assumed equivalent are as follows:

		Aircraft:
Traversed by ship:	Without difficulty	1-5/10 ice
	With difficulty	5-8/10
All but icebreakers brought to standstill:		8-10/10
Un-navigable:		10/10

The problem of bias in earlier 'historical' records should be carefully considered in any studies of trends in ice conditions (e.g. Ogilvie, 1984). Koch (1945, p. 167), for example, draws attention to some specific inadequacies in the Danish ice charts for Greenland waters. He also points out that a monthly chart must obscure important short-term variability in ice limits; moreover, what is depicted need not be representative of the average state for that month. Recent chart series from other sources tend to depict conditions at a particular point in time (e.g. end of month) rather than portraying monthly average conditions.

Current Data Products

Data Streams

Sea ice data on a worldwide basis are reported by synoptic observations on ships, by aerial ice reconnaissance patrols, and by satellite and occasionally submarine remote sensing. The ship observations are coded and reported in digital form; while the aircraft observations include coded observer reports, photography and processed imagery. The satellite data are multispectral scanning imagery. However, while they are received in digital form, they are processed to give imagery and then manually transferred to chart format (Figure 2). Much attention has been given to the digitization of such charts, although as shown in Figure 2, this process is not a trivial problem given the variety of types of data they contain. Current operational systems in North America now use digital data streams and work stations as described in the methods section on the National Ice Center's 7-day ice charts.

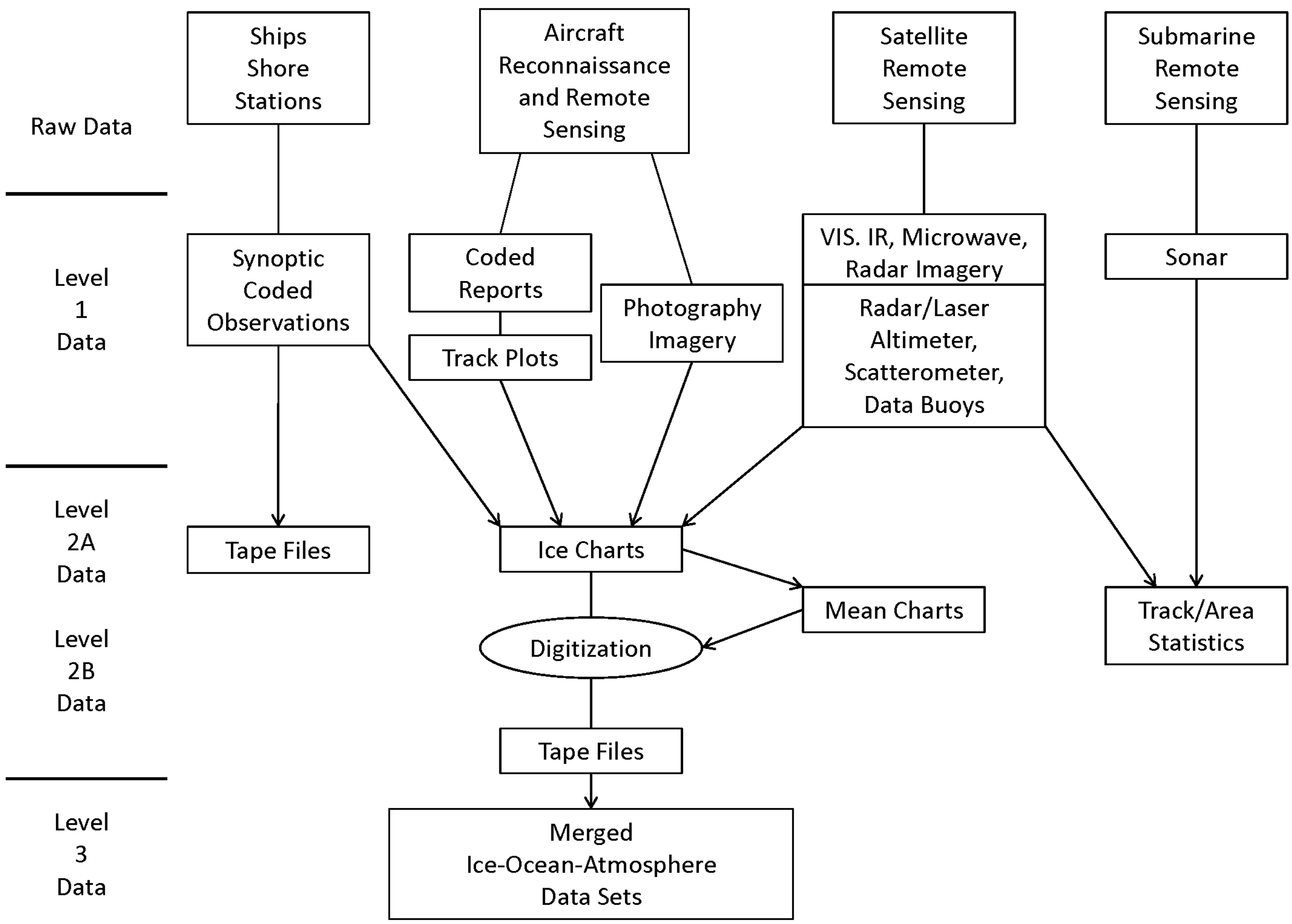

Figure 2. A schematic diagram of sea-ice data streams. The data levels in the left column refer to GARP categories of data processing.

Data Products

The variety of regularly-produced ice charts is summarized for hemispheric and regional products in Tables 1 and 2. A listing of national sea-ice information services and publications has been published by the World Meteorological Organization (1981). The most substantial ongoing analysis programs are those of the U.S. Navy-NOAA Joint Ice Center for both polar regions (U.S. Fleet Weather Facility, 1976a, b, and subsequent annual publications by the Naval Polar Oceanography Center – now the National Ice Center).

Table 1. Hemispheric Charts

Source	Parameter	Region	Record Length	Temporal Resolution	Chart Scale	Comments
U.S. National Ice Center	Ice concentration (tenths) Ice type	Eastern and Western Arctice and Antarctic	1972-present 1973-present	Weekly	1:11.6 million chart 1:11.6 million chart	Regional analysis available online since 1996
U.S. NASA-GSFC	Ice concentration (percent) from ESMR and multiyear fraction from SMMR	N. Hemisphere S. Hemisphere	ESMR 1973-76 SMMR 1978-87	ESMR - 3 day SMMR - alternate day	Gridded 50 km Gridded 25 km	
U.S. NSIDC	Ice concentration (percent) from SSM/I	Arctic and Antarctic	1987-present	Daily	Gridded 25 km	Distributed by CD-ROM
U.K. Meteorological Office	Ice concentration (tenths) iceberg areas, sea surface isotherms	Most of N. Hem except S.E. Bering and S'n Okhotsk Seas	1962-76	Monthly	1:22 million through 1967; 1.21 million 1968-76	1966-75 Digitized for most of area charts

These weekly analyses illustrated in Figure 3 draw on a wide variety of sources, including the microwave imagery collected for research and development purposes by NASA. It is worth noting that nowadays most national agencies draw heavily on United States satellite data. Hence, close similarity in most of the information depicted is to be anticipated.

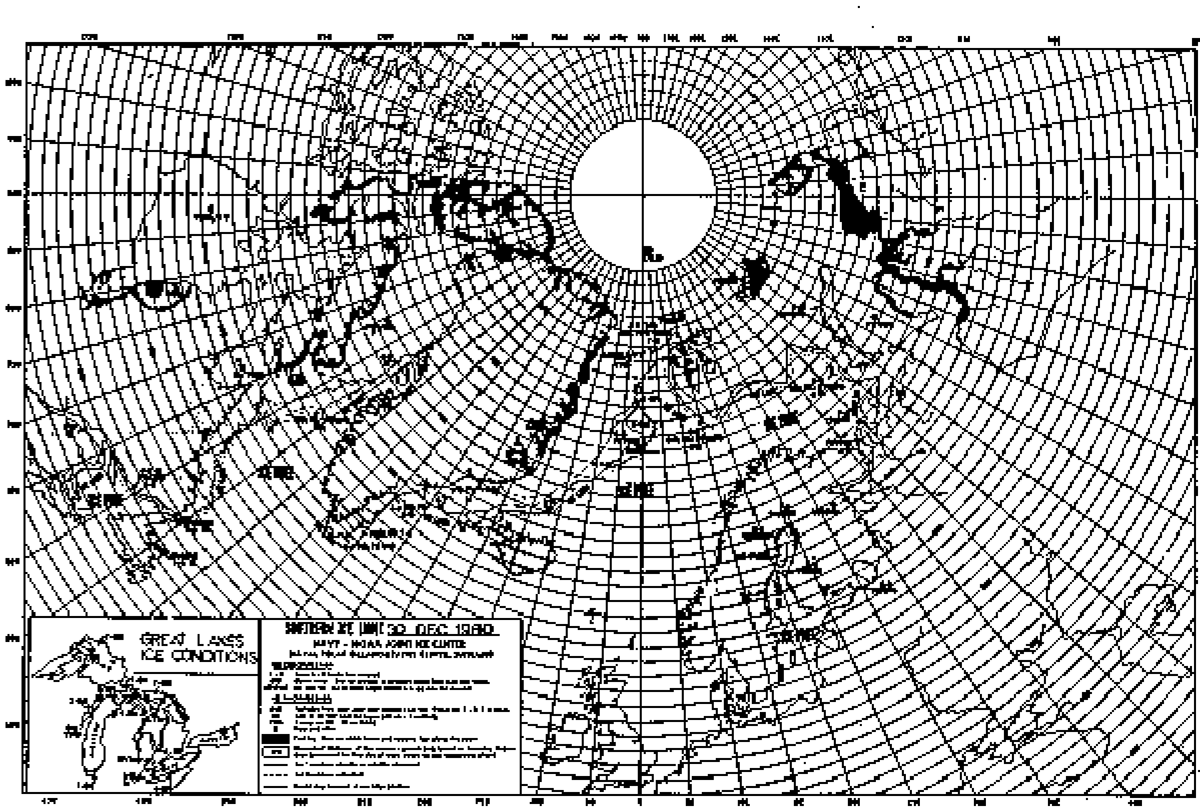

Figure 3. The southern ice limit for 30 December 1980 as depicted by the Navy-NOAA Joint Ice Center Chart.

The principles of remote sensing in relation to sea ice are discussed by Carsey and Zwally (1986) and for microwave data see Carsey (1992). From the mid-1960s through the 1970s most sea ice analyses depended on visible imagery (McClain, 1978). The weekly charts of the northern hemisphere snow and ice boundary produced by NOAA-NESDIS since November 1966 used visible imagery until January 1971 and infrared scanning radiometer data in conjunction with the visible channels thereafter, except for intervals of system failure (see Crane, 1979, p.64, for details). The analyses based only on visible data are necessarily incomplete in high latitudes during the period of polar darkness.

Essentially complete coverage of the polar regions with microwave data has become available since the launch of the Electrically Scanning Microwave Radiometer (ESMR) on Nimbus 5 in December 1972 and the Scanning Multichannel Microwave Radiometer on Nimbus 7 in 1978. Orbital data using an operational algorithm are available to the National Ice Center in near-real time. Research products have been produced from ESMR (see Digitization). However, the use of the dual-polarized multispectral SMMR data permitted the mapping of ice concentration, multiyear ice fraction and ice surface temperature with a 50 km resolution for 1978-1987. The SMMR data are available for individual frequencies and as ice concentration products in 25 km gridded form for October 1975-August 1987 on alternate days (NSIDC, 1994). Beginning in June 1987 the Special Sensor Microwave Imager (SSM/I) on Defense Meteorological Satellite Program (DMSP) satellites has continued to provide similar gridded daily, monthly ice concentration data with 25 km resolution (and 12.5 km for ice edge delineation) (NSIDC, 1995).

Regional analyses, such as those for the Baltic Sea and Canadian Arctic (Table 2) provide much more information on ice types, the occurrence of ridging, etc., than is possible on the hemispheric analyses. The problem of how this information could be integrated into more spatially-extensive digital data sets has not yet been addressed.

Table 2. Regional Charts

Source	Parameter	Region	Record Length	Temporal Resolution	Chart Scale	Comments
Canada, Atmos Environ. Service	a) Composite ice charts ice concentration (tenths) b) Historical Series ice concentration	Eastern sea-board Hudson Bay E. Arctic W. Arctic Great Lakes North of 65^{o} N Eastern Sea Board Hudson Bay Foxe Basin	1968 – present 1971 – present 1969 – present 1960 – 74 1958 – 74	2-7 days Dec-Jun 7 days Jun-Nov 7 days Jun-Oct 7 days 7 days May-Oct 7 days Dec-May	1:4 million 1:5 million 1:6 million 1:6 million	Digitized 1968-96 Digitized 1971-96 Digitized 1978-96 Digitized 1969-94 Digitized Few data N of 55^{o} N Digitized
Danish Meteorol. Institute	Composite ice charts Ice concentration (tenths)	North Atlantic Greenland waters	1901-39 and 1946-56 1957-81	Summer months (monthly) monthly and daily/weekly	1:13 million	Up to 1956, covering Arctic Seas. 1957-81 Greenland waters and all individual ice recon charts.
Norwegian Meteorol. Institute	Ice concentration (oktas); sea surface isotherms	North Atalantic 30^{o} W – 69^{o} E	1970 - present	3-4 days	1:10 million	
Russia: Arctic Antarctic Research Insitute	Ice concentration, types	European Arctic	1950 - present	10 days	1.5 million	Current maps on AARI web pages – gridded version in GDSIDB (1950-1992)
Swedish Met. Hydrol. Inst.	Ice conditions (9 categories of type, form, concentration)	Baltic Sea and Danish waters	1953 - present	3-4 days Oct-May/Jun	1:4 million	A 1:2 million facsimilie chart is prepared daily
Institue of Marine Research, Finland	Each series now uses the Baltic Sea code	Baltic Sea	1920 - present	Oct 15 – May 31	1:4 million	Digitized records of chart data, 1951-79
Deutsches Hydrographic Inst.		Baltic Sea and Gulf of Finland Western Baltic – German Bight	???	3-4 days Oct-May/June 2-3 days	1:3 million ???	
U.S. NIC	Ice concentrations (tenths), types (4 classes)	Great Lakes, North America	1962 - present	2-3 days	1:400,000 to 1:3 million	Digitized

U.S. NOAA-NESDIS	Ice concentration (oktas), types (6 classes)	Beufort-Chukchi Seas Chukchi-Bering Seas	1973-79	3-4 days	1:10 million	Discontinued
Argentina Navy Hydrographic Service	Ice edge, concentration	Bellinghausen Sea-Antarctic Peninsula-Weddell Sea sector (20-100 W)		3-4 days	1:5 million	
Japanese Weather Association	Ice concentration (oktas classes), sea surface isotherms	Sea of Okhotsk	Dec. 1973-83	3-4 days	1:9.5 million	
Japanese Meteorol. Agency, Maritime Meteorol. Division	Ice condition chart (tenths), sea surface isotherms	Sea of Okhotsk	Dec. 1938-present	3-4 days Dec. - May	1:12 million	Digital data (5-day) in GDSIDB 1972-98

Data on other ice parameters such as thickness, or motion, mostly exist in specific research publications. In the former case, limited information can be derived from data on ice types, but specific measurements are also available from field programs (Koerner, 1973) and from sonar studies (Wadhams and Horne, 1980; McLaren, 1989). The AIDJEX project first developed substantial statistics on the ice thickness frequency distribution and ice motion in the Beaufort Sea (Thorndike *et a*l., 1975), but it is recognized that there may be considerable differences in other sectors of the Arctic Basin. It should be remarked that even seasonal mean thickness is poorly known (Bourke and McLaren, 1992) and the question of trends in ice thickness is controversial (McLaren *et al.*, 1992;1994; Shy and Walsh, 1996; Wadhams, 1997).

The mean ice motion field in the Arctic Ocean has been determined from analysis of ice station drift patterns, (primarily from 1950-1990) combined with drifting buoys (from 1979-present) (Colony and Thorndike, 1984). Limited area mapping over short time intervals is possible by tracking ice floe features on AVHRR data, but these are often restricted by cloud cover. Sea ice motion products for the Beaufort-Sea sector derived from synthetic aperture radar (SAR) are available from the European Remote-sensing Satellite (ERS)-1 for winter months September 1991-December 1994. These were developed using a Geophysical Position System (GPS) at the Alaska SAR Facility in Fairbanks. Work is in progress to provide similar weekly products over the Arctic on a 50km fixed grid, together with histograms of ice age and thickness and fractions of multiyear ice and open water from the Radarsat GPS for winter 1996/97 onward. Samples of these products are currently available. Rather surprisingly, the use of daily SSM/I 37 and 85 GHz data has provided a capability for Arctic-wide mapping of ice motion (Agnew *et al.*, 1997; Emery *et al.*, 1997; Kwok *et al.*, 1998). The blending of buoy data with satellite data of varying spatial and temporal resolution suggested by Maslanik et al. (1994) affords a means of complementing the merits of the individual systems.

Recently, attention has focused on remote-sensing mapping of individual sea ice components or parameters including leads (Lindsay and Rothrock, 1995; Miles and Barry, 1998), albedo

(Robinson *et al*., 1992; Lindsay and Rothrock, 1994), melt inception (Anderson 1987; Winebrenner *et al*., 1994; Smith, 1998) and melt ponds (Fetterer and Untersteiner, 1998).

Special Data Sets

Special programs such as the Bering Sea Experiment (BESEX) (Kondratyev *et al*., 1975), Arctic Ice Dynamics Joint Experiment (AIDJEX) (Untersteiner, 1980), and even ongoing operational programs, like the International Ice Patrol in the western Atlantic (Anonymous, 1981) and the Great Lakes ice program of NOAA-Great Lakes Environmental Research Laboratories (World Data Center-A for Glaciology, 1980), generate multi-faceted data and the problem of their archiving has only recently received attention.

The multidisciplinary data collected in the East Greenland Sea-Fram Strait area through the Marginal Ice Zone Experiment (MIZEX) and the subsequent coordinated Eastern Arctic Research Experiment (CEAREX) are assembled on CD-ROM (NSIDC, 1991). Similar data sets will be developed through the 1997-98 Surface Heat Budget of the Arctic (SHEBA) field experiment in the Beaufort Sea.

The summarizing of display information produced by coastal radar stations on ice distribution or ice drift, such as that for Hokkaido (Tabata *et al*., 1980) also presents new problems, especially for comparisons with earlier data (Hakodate Marine Observatory, 1955). In general, it is preferable to archive ‘raw’ data (the lowest level of data useful to other prospective users), since the most appropriate calibrations of, say, sensor systems may not be immediately known, or improved data treatment becomes possible at a subsequent date. However, the computer software necessary to read special tapes (or other media) sometimes becomes unavailable after a certain time interval and the original data are then irretrievable. This is the case, for example, with airborne radar data collected by NASA Lewis over the Great Lakes. In other instances, routine satellite data received with extremely high resolution cannot all be archived. The Geostationary Operational Environmental Satellite (GOES) system has a data rate of 1 million bits per second, for example, necessitating time and space sampling (Jenne, 1981). There are similar problems with the synthetic aperture radar data collected by the ERS-1 and 2 and Radarsat.

Ice Indices

Many of the longer series of ice data have been compiled in the form of indices, usually as annual values. Table 3 (after Barry, 1986) summarizes most of the regional ones and indicates the variety of parameters selected. A few examples of different indices are discussed.

Table 3. Sea Ice Indices

Region	Parameters	Time Interval	Period of Record	Source
Geographic sectors: (see text) N. Hemisphere S. Hemisphere N. Hemisphere	Ice area (km^2) ≥ 1/8 concentration and percent open water in pack	 Weekly Monthly	 1972 → 1973 → 1960 →	Kukla and Gavin (1979) U.S. Navy charts British Met. Office
Arctic (sectors)	Area (km^2) between limit of 7/10 ice and minimum extent; graphs	Monthly; Feb-Apr Aug-Sep	1966-1974 (Atlantic sectors) 1969-1974 (Pacific sectors)	Sanderson (1975) British Met. Office charts
Greenland-Barents- Kars seas	Ice occurrence weighted for each area (see text)	Annual for Apr-Aug	1895-1924	Brooks & Quennell (1928) from Danish data mainly
Greenland-Barents- Seas and Spitsbergen area	Severity index (-7 to +7) estimated for each of three sectors and mean tabulated (2 estimates)	Annual	1897-1938	Walker (1947)
Greenland Sea	a) Area b) Area (44°W-15°E) deviations from average for 1898-1913; graph c) Percent of area (monthly and seasonal)	Apr-Aug Apr-May Apr-Aug Apr-Aug	1877-1915 1900-1939 1946-1957 1924-1939 1945-1968	Speerschneider (1917) Skov (1970) Kirillov & Khromtsova (1972) from Danish data and "Marine Observer"

West Greenland (Davis Strait)	a) N'wd extent of Storis b) N.most extent; W.most extent of Storis; index 0-10 from extent for each mon and duration summarised as annual mean c) Ice area W. of 44°W (weight of cut-out paper traced from maps)	Annual Annual for Jan-Aug Apr-Aug	1821-1939 1900-1972 1820-1930 1901-1937	Kock (1945) Valeur (1976) Speerschneider (1931) from ships logs and Danish annuals from 1897. Hansen & Svistrup (1943) from Danish maps
Newfoundland	a) Index of sea ice area; (Lat. of E.most extent + Long. of S.most extent), 87 max. to 103 (min. ice) b) Severity index for sea ice (-2 to +2)	Apr Annual ? Spring	1920-1973 (except 1940-1943) 1860-1902	Miles (1974) from British Met. Office, U.S. Coast Guard and "Marine Observer" Meinardue (1905) from British, German and North American data
West Atlantic	a) Iceberg number S. of 48°N b) Iceberg severity index (N/24-13/2, where N=number of icebergs	Annual Sep-Aug Mar-July	1900-1970 1886-1939	Bailey (1972) U.S. Coast Guard data Walker (1947) from Mainardos and U.S. Coast Guard
Iceland	a) Duration of drift ice at coasts with 3 categories of width of ice belt E-W; monthly ice maps	Monthly	1877-1939 1940-1971	Kock (1945) from Thoroddsen, Sigtrygsson (1972) updated by Lamb (1977)
Baffin Bay	Date of total clearing of sea ice	Annual	1952-1970 1952-1976	Dunbar (1972) updated by Keen (1980)
Barents Sea	a) Ice area b) Ice area as % of Barents Sea	Apr-Aug May-Aug	1895-1915 1900-1960	Danish Met. Inst. (1917) Maksimov et al. (1964)

Kara Sea	a) Ice area b) Severity index (-2 to +2)	Apr-Aug Unspecified	1895-1915 1868-1946 except 1885, 1891-1892 (some data back to 1530)	Danish Met. Inst. (1917) Nazarov (1947)
Beaufort Sea	Severity index; ranking of years based on 6 features—distance to pack-ice off Barrow, conditions along ship route to Prudhoe Bay	Aug-Sep	1953-1975	Barnett (1976) from U.S. Navy data
Okhotsk Sea	Anomaly of drift ice (days) at Abshira and at Shana, Hokkaido Dates of appearance/ disappearance of fast ice and pack ice at 7 coastal stations	Dec-Apr Dec-Apr	1892-1945 1959 → (and less complete earlier data)	Sawada (1957) Bulletin of the Hakodata Marine Observatory (No. 20, 1981) (annual reports)

Several indices describe the maximum ice extent, including those for Newfoundland (Miles, 1974) and West Greenland (Koch, 1945; Valeur, 1976, and Speerschneider, 1931). As recognized by Koch, however, ice drift is a complex variable which particularly reflects wind velocity. Other studies define ice "severity" by a relative scale. Some of these are not readily interpreted since no examples of the selected scale are given. This is true of the historical series for the Kara Sea (Nazarov, 1964), and the indices of Walker (1947), Meinardus (1905, 1906), and Brooks and Quennell (1928). The last authors develop a weighted index (I) of ice conditions in the Greenland (G), Barents (B), and Kara (K) Seas, partly according to partial regression coefficients relating the ice to atmospheric parameters. The index is:

$$I=5(G_{5\text{-}8}) + 7\,(B_{5\text{-}8}) + [3K_8 + K_{5\text{-}8}]$$

where the subscripts denote the months considered.

i.e., $G_{5\text{-}8}$ denotes the ice conditions in the Greenland Sea in May through August.

Several problems need to be recognized with regard to ice indices. First, there is the question of the reliability and representativeness of the data used in historical sources. This point has already been discussed. Second, many of the indices are seasonal averages which may obscure crucial differences between different years. Also, such averages may be biased due to the equal weighting of the monthly data that they incorporate. A third difficulty with indices concerns their spatial representativeness if, for example, the ice anomalies are of opposite sign in different sectors of a large region such as that used by Brooks and Quennel. A fourth problem may arise when a single date is used to define some stage of the seasonal ice cycle. This is illustrated by the identification of the "final ice clearance" in Baffin Bay (Dunbar, 1967; Keen, 1980). Its timing may be difficult to determine in the first place and its physical significance is complex since this stage marks the culmination of a protracted process involving thermodynamic and dynamic processes (Dey, 1980). The typical decay stages for fast ice in the same region, which can be related to meteorological parameters, have been defined by Weaver *et al.* (1975).

The most comprehensive indices are those of Kukla and Gavin (1979). Digital files of ice area and the percentage of open water within the pack have been developed for geographical sectors in both polar regions. The weekly U.S. Navy ice maps are used since 1972 for the Arctic while the British Meteorological Office maps are used to provide a monthly file of Arctic ice area since 1960. A limitation of these indices is their use of geographical sectors ca. 10º latitude meridionally by a variable longitudinal span.

Digitization

The need for cryospheric data to be readily accessible in digital form is now widely acknowledged (WDC-A for Glaciology, 1979; Kukla *et al*., 1981), but only limited progress has been made in this direction as indicated in Tables 1 and 2. On the practical level the digitization process involves prior decisions as to the projection or grid to be used, and the element size and resolution appropriate to the data. Commonly used grid arrays for the meteorological archives are the U.S. National Meteorological Center (NMC) grids, but these are not equal area. It was recommended by the Snow Watch Workshop that projection (x,y) coordinates be used for archiving digital information with appropriate documentation provided to transform the data into geographical coordinates (Kukla *et al*., 1981). An Equal Area Scalable Earth (EASE) grid developed by Armstrong and Brodzik (1995) is now being used for many NSIDC data products and the AVHRR, TOVS, and SMMR/SSM/I Polar Pathfinder products (Barry, 1997).

Several sets of digitized monthly ice data are now available. Extending work by Kelly (1979) for the Northern Hemisphere, Walsh (1978) has extracted ice concentration values on a 1º grid using a variety of sources for 1901-1995. Corresponding meteorological data grids are also available. The data quality is recognized to be spatially and temporally variable especially in the first half of the century. Moreover, the data are "end of month" values not monthly averages.

For Arctic and Antarctic ice conditions (on a common base) there are now several digital data sets. One has been extracted by Lemke et al. (1980) from monthly charts of the British Meteorological Office for the Arctic for 1966-1976. The parameter in the Arctic is the area of ice per 10º longitude x 1º latitude sector; each 1º rectangle is counted as ice-covered where $\geq$7/10 ice is shown. Another set comprises the digital 3-day average microwave brightness temperature data obtained by NASA from the Electrically Scanning Microwave Radiometer (ESMR) system on Nimbus 5 and 6 satellites. The data array is a 293 x 293 grid with an approximate 50 km resolution. These data are available for about 85 percent of the time from December 1972 through May 1977 (except for March-May 1973 and June-August 1975) from ESMR 5 and for parts of the period August 1975-July 1977 from ESMR-6. The SMMR data from Nimbus 7 for October 1978-August 1987 and SSM/I data from the DMSP satellites from July 1987-present are archived at the NSIDC.

An additional set of digital data has been prepared by the U.S. Naval Oceanographic Office (Westhall, 1975). Visual observations from the BIRDSEYE ice reconnaissance flight and other missions in the Arctic during 1964-72 have been coded and filed in sectors 2º latitude by 10º longitude. The files include location, time, ice, concentration, the primary ice form (floe size), stage of development and fractional concentration, topography, extent of ridging, opening, and number of bergs in three size categories.

Through a sustained effort by the Subgroup for Sea Ice of the Commission on Maritime Meteorology, WMO, digital archives for both polar regions comprising the Global Digital Sea

Ice Data Bank (GDSIDB)are now held by the Arctic and Antarctic Research Institute, (AARI), St. Petersburg and World Data Center for Glaciology, Boulder, Colorado. The archives include AARI data on ice concentration and ice type for the Eurasian Arctic at ten-day intervals 1953-1990 in SIGRID-1 and EASE-grid, and weekly U.S. National Ice Center Data for the Arctic for 1972-94 and the Antarctic for 1973-91. Updates to these records are being prepared. There are also annually updated ice extent data from the Japanese Meteorological Agency for the Sea of Okhotsk.

Ice Atlases

In addition to time series and spatial patterns for individual months, it is also necessary to have long-term average distributions of ice extent. Published atlases of sea ice include ones for the Northern Hemisphere (U.S. Navy Hydropraphic Office, 1946), Arctic Canada (Swithinbank, 1960; Markham, 1981), Alaska (LaBelle et al., 1983), the eastern Canadian seaboard and archipelago (Markham, 1980; Sowden, Geddes, 1980), seas north of the USSR (Armstrong, 1958), the Baltic (Swedish Meteorological and Hydrological Institute, 1982) and ones derived from ESMR and SMMR passive microwave data for the Arctic (Parkinson et al., 1987; Gloersen et al., 1992). In addition, general atlases of the polar regions usually depict at least the mean seasonal ice limits. A new Atlas of World Snow and Ice Resources including sea ice maps has recently been published (Kotlyakov, 1998). Walsh has also developed a long term time series of monthly ice charts on a one degree grid for the period 1901 - 1995 which integrates many of very early ice charting records with more recent satellite observations (Walsh et al., 1978).

Two principal types of map display of ice information have been used up to now (Armstrong, 1964). Isopleths of average and extreme limits at specified time intervals are the most common (Sowden and Geddes, 1980), but sector (‘pie’) diagrams of relative frequency located at points, or for box areas, have been used by Armstrong (1958) and Swithinbank (1960). The ice limit may be for > 1/8 or some other concentration. In the case of the ESMR and SMMR atlases, the 15 percent concentration is approximated from microwave brightness temperatures. These data sources provide continuous monitoring of global sea ice conditions although careful cross-calibration between the sensors is required (Stroeve et al., 1998).

Other regional presentations of mean monthly ice limits are available in yearbooks, journals, and reports. Some examples include studies for the Bering Sea (Dunbar, 1967; Webster, 1981), the Okhotsk Sea (Watanabe, 1967), the North Atlantic-Barents Sea sector (Vinje, 1977), the Baltic (Palosuo, 1966), and Hudson Bay (Danielson, 1971). For icebergs off Labrador, mean seasonal maps of relative densities have been published (Gustajtis and Buckley, n.d.). An atlas of icebergs in the Arctic is also now available (Abramov, 1996).

Data Needs

As a basis for evaluating existing sea ice data, or for assessing future requirements, it is essential to consider the types of use to which these data are put. For example, detailed local data on ice extent, concentration, thickness, and motion are required in "real-time" for operational purposes, such as navigation. These and associated meteorological/oceanographic data are also used in short-term forecasting of ice conditions for shipping. Similar types of data are needed over a number of years in particular localities for operational or commercial purposes to assess the probability of certain ice conditions occurring at a given time of year. Such assessments may also require data on the frequency of open water, ridged ice, etc.

From the research standpoint, sea ice is an important component of the oceans and of the climate system. Most general circulation models (GCMs) of the atmosphere now incorporate sea ice cover effects at least as a fixed surface boundary condition. The ice is expected to influence the occurrence of cyclone activity in the models, although the nature of such interactions is inadequately known. For atmospheric GCMs, gridded data are required on monthly mean ice concentrations with a resolution of at least 100 km. To adapt such models for extended-range (7 day) weather-forecasting purposes would necessitate the availability of at least weekly ice data on a routine-basis. Coupled models incorporating sea ice – atmosphere interactive systems have been developed building on present knowledge of the operative thermodynamic and dynamic processes. Sea ice models have also been tested using climatological mean forcing by the atmosphere (Parkinson and Washington, 1979; Hibler, 1980) and daily wind forcing)Walsh *et al*., 1985; Hakkinen, 1994) with improved treatment of ice dynamics (Lemke *et al*., 1997; Weatherly et al., 1998). Multi-decadal simulations of Arctic sea ice variability can be performed and used to generate data that can be evaluated against satellite, buoy and sonar measurements (Chapman *et al*., 1994) In the case of the mean ice conditions, adequate verification data exist for ice extent, although not for ice thickness, and studies attempting model simulations for individual years encounter inadequacies in the available data (Walsh et al., 1984). Also, there are major problems of the adequate parameterization of sub-grid scale processes, such as heat fluxes from leads or thin ice, in the lower boundary region of the models.

The parameters that characterize sea ice conditions are listed in Table 4 with an indication of the typical levels of accuracy, spatial and temporal resolution required for purposes of basic research, and climatological studies. However, these levels may be inadequate for other purposes such as shipping operations. For assessments of ice forces on structures, and other hazards relating to ice motion, information on ice mechanical properties and on meteorological/oceanographic factors is necessary.

For many of the parameters listed in Table 4, the "data base" is limited to the published results of specific research investigations and data sets, as such, are non-existent. Most of the requirements shown in Table 4 are within the technical capabilities of present measurement systems, although many of these systems are not yet operational and indeed may not become so within the next several years.

[1]Table 4. Basic Requirements for sea ice observations (after NASA, 1979, with modifications)

Parameter	**Accuracy**	**Resolution (Space)**	**Resolution (Time)**	**Sensor Type(s)**	**Comments**
Ice Boundary	5-20 km	5-20 km	1-3 day	SAR or passive microwave, multi-frequency	Imaging radar for high resolution

Concentration	2-5%	25-100 km	1-3 day	Passive microwave, multi-frequency	Imaging radar for high resolution
Type (fractional area by type) orientation	5-10%	25-100 km	7-30 day	SAR or passive microwave, multi-frequency	Gives some thickness information
Leads: fractional area orientation	5-10% 10-30 deg	5-25 km N.A.	1-3 day 1-3 day	SAR	
Ice Thickness	0.2-1 m	25-100 km	7-30 day	Sonar	Occasional measurement (submarine or moored upward looking sonar)
Motion (point displacement)	0.1-1 km per day	5-100 km	1-7 day	Data buoy: visible, passive microwave and imaging radar	Routine products with Radarsat
Ridging: Density Height Orientation	10-50% 1 m 10-30 D	5-25 km N.A. N.A.	7-30 day 1-30 day 7-30 day	Imaging sonar	Scatterometer; Sonar
Albedo (areal mean)	0.02-0.04 (5-10 %)	25-100 km	3-10 day	Scanning multiband radiometer	AVHRR Polar Pathfinder
Surface Melting (fractional area)	Wet/dry	100 km	1-3 day	Passive Microwave	
Surface Temperature	1-3 K	25-100 km	1-3 day	Scanning multiband radiometer	AVHRR Polar Pathfinder
Icebergs: Location Volume discharge (ocean current system)	 100 m 5-10%	 Area average	 6-48 hour 3-12 months	 Imaging radar	 Location for operational needs around offshore platforms
Arctic Meteorological Data: Surface Pressure (point) Wind velocity (point) Air temperature	 0.5-1 mb 10-20d, 1-2 ms^{-1} 0.2-1 K	25-50 km	3 hour	Sensors on Drifting Buoys	International Arctic Buoy Programme
Sea surface temperature	0.2-2 K	10-25 km	1-3 day	Scanning multiband radiometer	Current global products are of limited accuracy in the marginal ice zone

[1]Smaller value is desired standard; larger value is minimum for basic climate studies. One or the other may be more appropriate to location and season.

A major problem with most existing ice data is that they are not readily meshed with concurrent meteorological and oceanographic information. Few "Level 3" data sets (see Figure 2) have been compiled, in part because most research projects tend to be uni-disciplinary, and in part because of the multi-organizational nature of data collection and archiving relating to sea ice and the associated atmosphere/ocean conditions. The Arctic Ice Dynamics Joint Experiment (AIDJEX) provided a rare exception to this statement and the data deriving from this project are well documented (Stateman, 1978). All of the AIDJEX data that could be recovered are archived at NSIDC. Nevertheless, the time span of AIDJEX was limited.

Coupled ice-atmosphere data sets have been prepared on a monthly time scale by Walsh, but meteorological observations in the polar regions are inadequate for detailed synoptic scale studies. Even for many of the remote sensing analyses of ice conditions, there are insufficient ground-truth data to verify the existing interpretations (e.g. Crane *et al*., 1982).

Data Problems and Future Prospects

Some of the complexities involved in securing useful data bases on sea ice are readily apparent from the foregoing. A major difficulty is posed by the continual improvement of the sensor system. Historically, the observational records have changed emphases from shore station, to ship observations, to aerial reconnaissance support, and finally to global coverage via satellite remote sensing. The ‘matching’ of different types of data is rarely considered, yet this presents serious problems in attempting to define any changes in ‘typical’ or mean conditions. This was noted by Gloersen *et al*. (1974) in comparisons of early microwave results with ice atlases depictions of ice extent. However, the higher spatial and temporal resolution of each succeeding generation of instrumentation will cause this problem to keep recurring. Indeed, there may be a case for ‘degrading’ high resolution data for purposes of historical comparisons. An alternative may be to devise or adopt suitable regional indices of ice conditions of the type described above.

Another general problem is that the standard parameters characterizing sea ice may be inadequate for process-oriented studies at the frontiers of basic or applied research problems. It is, nevertheless, impossible to develop all-purpose data bank structures to take account of all possible future requirements. New data files must be developed as new data types are generated.

The procedures involved in establishing and maintaining data bases are as follows:

1. The data need is identified (e.g. by the user community).
2. Existing data sources are determined (e.g. by a workshop and an inventory).
3. Data files are transferred to a data center.
4. Documentation/data formats are checked or set-up, if not available.
5. Archived data are advertised (data fliers, catalogs) and distributed to meet requests, on appropriate media or via the web or file transfer.
6. Data files are updated periodically.

The focal point for such activities is normally a data center. In many countries, sea ice observations are the responsibility of the national meteorological or hydrographic service but most of these data are available only in chart form, as noted earlier. Standards for ice observing codes and chart displays are prepared and reviewed by a Working Group of the Commission for Maritime Meteorology of the World Meteorological Organization (WMO, 1997). This group oversees the Global Digital Sea Ice Data Bank (GDSIDB) described in Digitization (above). The international exchange of sea ice data is formally identified as the responsibility of the World Data Center for Glaciology in Boulder, Colorado, and the Arctic and Antarctic Research Institute in St. Petersburg, Russia.

Major bibliographic references include WDC for Glaciology (1978), and Bradford and Moline (1980). The National Snow and Ice Data Center maintains extensive files of digital crysopheric data, as well as documenting what archives exist elsewhere. Some of the specialized types of data referred to earlier may not be covered by these routine types of observation. Recent large projects have recognized the need for careful pre-planning of data management operations and within governmental agencies data archiving is normally a routine operation. Even so, experience shows that potential scientific users are not always aware of the availability of archived data and the existing data formats may not be optimal for their needs. Moreover, the data products of individual scientists or small research groups may not be retained, or formatted and documented in such a way that others can use them in the future. In these activities the data center system can play a crucial role.

It must also be pointed out that data storage, management and distribution involves costs, particularly where numeric data banks are involved. Jenne (1981) notes that the factors which enter into these costs include programming and processing, purchase and maintenance of computer hardware and its operation, software development and documentation, and floor space. The data storage costs depend upon the media used (tape, disk, mass storage system, and the frequency of access). For most cryospheric parameters, the data volume is not yet a serious problem, but the heterogeneity of data types and format and the problem of accessibility represent major obstacles to many scientists. The media involved in the case of sea ice parameters, for example, include log books, charts, track plots, coded observations, photography, multi-band imagery, digital files by satellite orbit as well as in grids, and analog sonar traces. Recognition of the potential future problems that may arise, if appropriate data management strategies are not devised, is the essential first step to well-structured data bases that can adequately serve the needs of users.

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