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U.S. National/Naval Ice Center Digital Sea Ice Data and Climatology

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RÉSUMÉ

Des cartes hebdomadaires de la glace de mer produites par le Centre national des glaces (NIC) de 1972 à 1994 ont été rendues publiques récemment en soutien à la recherche environnementale. Ces cartes étaient conçues à l'origine comme outil d'aide à la navigation pour les navires opérant dans les eaux infestées de glace de mer dans l'hémisphère nord. Toutefois, on a réalisé très tôt que ces données constituaient une ressource unique pour les chercheurs en milieu Arctique, apportant une contribution significative aux ensembles de données sur la glace de mer compilées par Walsh (1978) et autres. Les enregistrements de concentration de glace dérivés couramment des données des capteurs satellitaires hyperfréquences passifs sont semblables à l'ensemble de données du NIC en termes de résolution, d'étendue et de période d'enregistrement, mais ces ensembles de données hyperfréquences peuvent souffrir de biais systématiques reliés au processus et aux algorithmes de formation de l'image utilisés pour déduire la concentration de glace à partir des données brutes. Bien que l'ensemble des données numériques de glace de mer du NIC ait ses propres limitations, les premiers enregistrements dans le temps précèdent les enregistrements de données par capteurs hyperfréquences passifs et permettent d'éviter certains de ces biais inhérents. Cet article décrit les caractéristiques spatiales et thématiques de l'ensemble de données historiques du NIC de même que les données numériques et analogiques et les méthodes d'analyse utilisées pour créer l'ensemble de données. Cette étude analyse aussi brièvement les changements à long terme dans le couvert de glace dans l'Arctique. L'ensemble de données du NIC révèle que les patrons de concentration de glace de mer dans les secteurs Atlantique et Pacifique de l'Arctique varient en réponse aux changements dans l'Oscillation de l'Atlantique Nord. Ce résultat est cohérent avec les résultats des recherches d'autres chercheurs qui ont utilisé d'autres ensembles de données.

SUMMARY

Weekly sea ice charts produced by the National Ice Center (NIC) from 1972 through 1994 have recently been released to the public in support of environmental research. These charts were originally intended as navigation aids for vessels operating Northern Hemisphere sea ice-infested waters. However, it was recognized early on that these data represent a unique resource for Arctic researchers, adding significantly to sea ice data sets compiled by Walsh (1978) and others. Ice concentration records commonly derived from satellite passive microwave data are similar to the NIC data set in terms of resolution, extent and period of record, but these microwave data may suffer from systematic biases related to the imaging process and algorithms used to infer ice concentration from raw data. Although the NIC digital sea ice data set has its own limitations, its starting point precedes that of the passive microwave record and avoids some of its inherent biases. This paper describes the spatial and thematic characteristics of the NIC historical data set, as well as the digital and analog data and analysis methods used to create the data set. This study also briefly investigates long-term change in Arctic ice cover. The NIC data set reveals that sea ice concentration patterns in the Atlantic and Pacific sectors of the Arctic vary in response to changes in the North Atlantic Oscillation. This result is consistent with the findings of other researchers, who used other data sets.

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INTRODUCTION

From 1972 though 1994, the National/Naval Ice Center (NIC) in Washington, D.C. drew on resources from the U.S. Navy, National Oceanic and Atmospheric Administration, and the U.S. Coast Guard to fulfill its mission of providing global sea ice analyses and forecasts to the U.S. military and civil sectors. NIC customers, ranging from submarine captains to polar adventurers, researchers, and educators, relied on NIC's analog and digital sea ice charts and message products as guidance for mission planning, scientific studies, and real-time maritime operations in polar regions.[1]

The most widely-used products were the NIC weekly sea ice charts. These charts span the entire Arctic and sub-Arctic from 1972 to the present day. **Figure 1** illustrates a typical ice chart in original paper form (**Figure 1a**) and in digital form (**Figure 1b**). Russia, Japan, Denmark, Germany, Iceland, Norway, Canada and nine other nations share an interest in Arctic conditions and maintain records comparable to those of the NIC sea ice charts (albeit with more limited coverage) (Benner and Ramsay, 2000; Bertoia *et al*., 1998). With the international interest in increased safe navigation in ice-covered waters, ice charting standards were formalized in 1970 under the World Meteorological Organization (WMO, 1970). These standards have evolved somewhat since that time due to operational necessity, evolving data collection efforts and improved interpretive capabilities. However, the basic chart content has remained unchanged for more than 30 years.

Though not originally intended as an aid to scientific research, NIC's archive of charts summarizing weekly Arctic sea ice conditions from 1972 though 1994, constitutes a significant, untapped record of northern hemisphere ice cover. Until recently, the lion's share of this powerful data set lay dormant. The charts remained in their paper form, and many were unavailable to the general public for National Security reasons. In October 2000, however, these charts were released in the form of a digital spatial data archive suitable for climate research and other scientific applications from the NIC and the National Snow and Ice Data Center (NSIDC).

Long-term climate modelling and recent global climate research suggest that Arctic sea ice extent and thickness are sensitive indicators of climate variability (Vinnikov *et al*., 1999; Rothrock *et al*., 1999; Wadhams, 1994). To date, monitoring of Arctic sea ice has been carried out with data obtained from passive microwave satellite sensors such as the Electrically Scanning Microwave Radiometer (ESMR), the Scanning Multi-frequency Microwave Radiometer (SMMR), and the Special Sensor Microwave Imager (SSM/I). Unfortunately, these observations are affected by problems such as erroneously low summer ice concentrations resulting from surface melt (Steffen *et al*., 1992; Cavalieri, 1994; Meier *et al*., 2001). NIC's historical digital sea ice archive incorporates visible and infrared imagery that can resolve some of the uncertainty in the passive microwave ice concentration data record. In addition, these higher resolution data sources (particularly during later years) provide more detailed information on ice conditions. Finally, this data set extends the passive microwave ice concentration record back in time allowing a longer-term view of ice conditions in the Arctic.

Complementing the 23-year digital ice chart archive are gridded climatology fields, which are derived from high-resolution National Security data collected from 1972 through 1990. These grids contain summary statistics of monthly sea ice occurrence and monthly median ice concentration. These fields provide a higher level of detail than the individual charts or passive microwave satellite imagery alone because they incorporate information from higher-resolution classified sources.

This paper introduces the NIC historical Arctic sea ice data set and associated high-resolution climatology to the research community. It describes the spatial and thematic characteristics of the data set and discusses the data sources and analysis methods used to create these products. This article also illustrates the use of this data set for investigating Arctic climate variability.

23 YEARS OF WEEKLY ARCTIC SEA ICE CHARTS

Early History

Prior to 1950, "*in situ*" visual ice observations from coastal stations, transiting ships, and aircraft patrols were the only sources of data on sea ice conditions and iceberg[2] locations in the Northern Hemisphere. The U.S. Coast Guard's International Ice Patrol (IIP) was among those historically responsible for gathering and reporting information on ice hazards in northern navigable waters. The IIP formed in response to the recognized threat posed by icebergs to North Atlantic shipping lanes, and to prevent accidents like that which befell RMS TITANIC in April 1912. In 1951 sea ice earned recognition from the U.S. Navy as a hazard at least as significant as icebergs. It caused severe damage to a convoy of Navy ships navigating along the western coast of Greenland during the establishment of a Distant Early Warning Station and Thule Air Base, Greenland (Benner and Ramsay, 2000)[3]. As a direct result of lessons learned off western Greenland in 1952 and continuing through the 1960s, the U.S. Navy established a formal sea ice-monitoring program (based largely on aerial, shore-based and ship-borne reconnaissance). This activity eventually became what is known today as the NIC.

Remotely sensed data had been used as early as 1960 for sea ice analysis (Massom, 1991), but it was not until 1972 that remotely sensed data from early National Aeronautics and Space Administration (NASA) and National Oceanic and Atmospheric Administration (NOAA) satellites were routinely made available for use by NIC ice reconnaissance units. NIC immediately recognized the value of the images returned by satellites not only as a means of reconnaissance mission planning, but as a direct source for large-scale, higher-resolution sea ice mapping. Environmental satellites now provided NIC a

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[1] Prior to 1995, NIC was known as the Navy/NOAA Joint Ice Center (JIC).

[2] An iceberg is land ice of glacial origin.

[3] U.S. Navy ships of this convoy were conducting "Operation Bluejay."

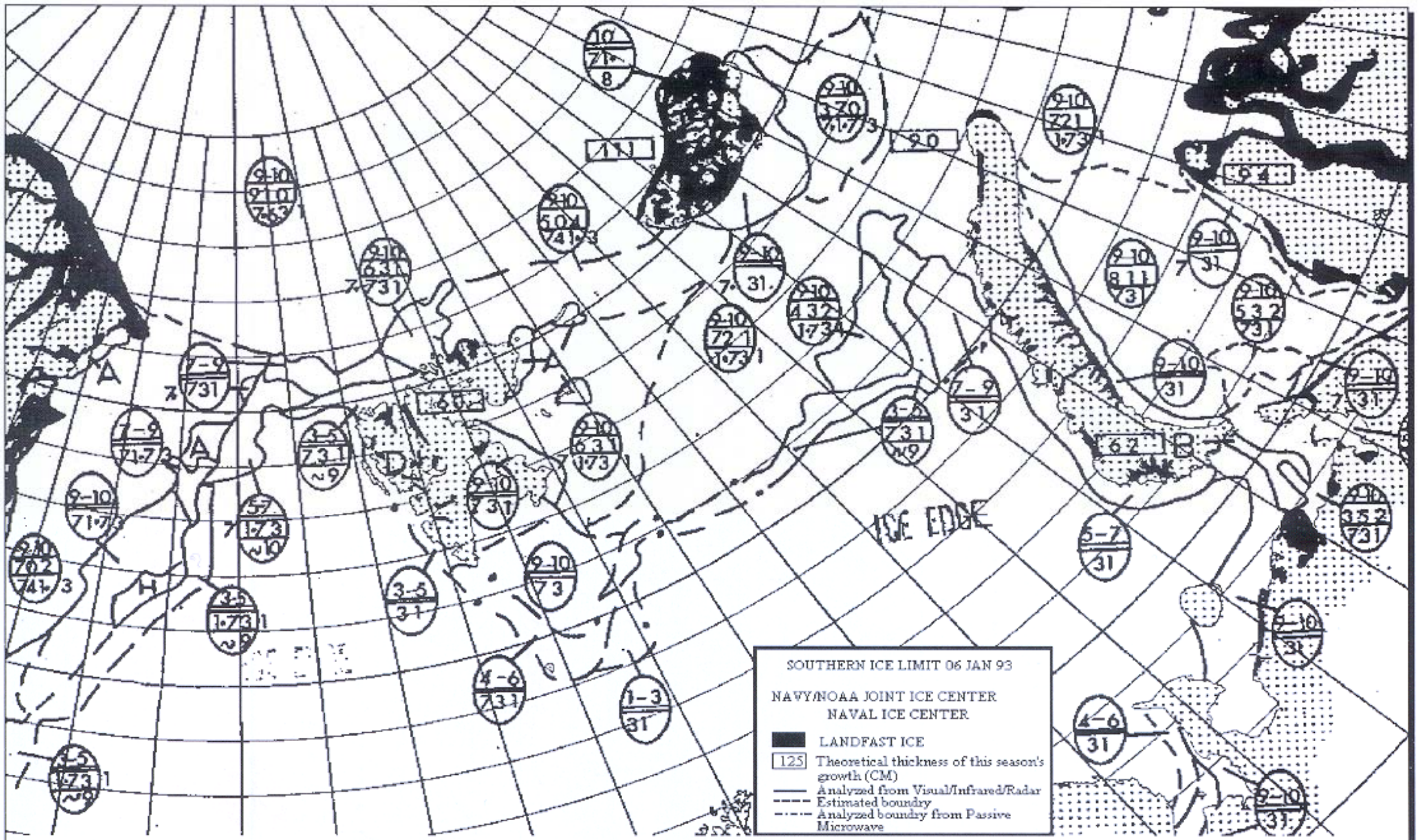

Figure 1a.
An example of a late 1980s / early 1990s era NIC Sea Ice Chart. During the 1980s and beyond, NIC reported total ice concentration, ice stage of development and ice form in accordance with the WMO "Egg Code" standard, which facilitated direct translation to SIGRID ASCII code during digitization.

means of almost continuous monitoring of ice conditions, though the interpretation of satellite imagery for ice mapping purposes would prove challenging for even the most experienced ice reconnaissance personnel. By the late 1970s, NIC put in place a reliable imagery interpretation and analysis training program, essential for the generation of consistent, accurate hemispheric sea ice charts on a weekly basis. Having established the convention of disseminating sea ice conditions in the form of geographic charts (in accordance with evolving ice charting standards set by the WMO), NIC and those who relied on NIC ice charts found them essential as a basis for meaningful mission-related decision-making, recommendations and forecasts for ships and submarines operating in Arctic waters. In addition, the global availability of satellite imagery made possible the recording of ice conditions over an entire hemisphere. Requirements for complete, detailed, hemispheric sea ice charts were based on three factors (Kniskern, 1991; Benner and Ramsay, 2000). They are:

1) NOAA's mission to help protect Alaskan commercial fishing;
2) The U.S. Navy's mission, which included submarine patrols in the Arctic as well as ongoing support missions to Thule, Greenland;
3) An increased scientific interest in monitoring changes in the polar climate.

Chart Content and Characteristics

Through 1994, NIC produced ice charts using traditional hardcopy cartography techniques, starting with base-maps produced by the Defense Mapping Agency (DMA) or the Naval Oceanographic Office (NAVOCEANO). Polar Stereographic, Lambert Conformal, Equal-Area Azimuthal, and Mercator projections were used for the base-maps depending on the scale, area of interest, and operational requirements. NIC represented sea ice on its charts as unique bounded regions ("polygons"), each of which contains homogeneous sea ice conditions, as determined by an analyst.

Driven by evolving maritime operational requirements, data sources, and international ice charting standards, NIC analysts produced charts of "ice concentration"[4] and (where justified by available data) "ice stage of development"[5] (usually including specification of partial ice concentrations associated with each ice stage of development). Analysts paid close attention to the locations of the limit of all known sea ice (the "ice edge"), the limit of pack ice (ice having greater than 95 percent concentration) and the limit of "old ice" (ice surviving more than one melt season). Analysts also historically captured information about certain ice forms, such as "fast ice" (sea ice

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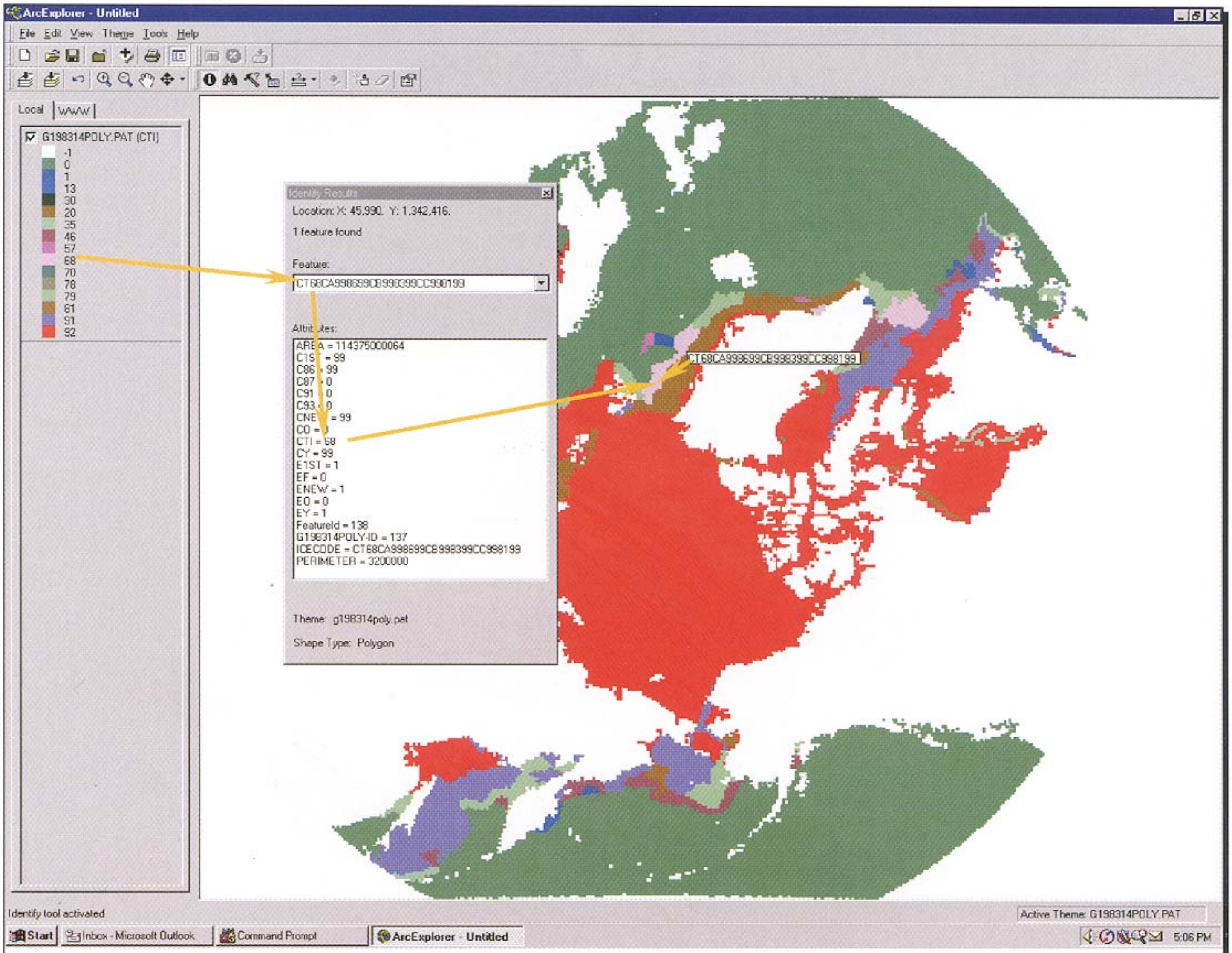
[4] Ice concentration was measured in "octas", or eighths, early on, and later measured in tenths, in accordance with WMO guidance (WMO, 1989).

[5] Ice stage of development relates to ice age and thickness (WMO, 1989).



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1 feature found

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C86 = 99
C87 = 0
C91 = 0
C93 = 0
CNEW = 99
CO = [illegible]
CTI = 68
CY = 99
E1ST = 1
EF = 0
ENEW = 1
EO = 0
EY = 1
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ICECODE = CT68CA998699CB998399CC998199
PERIMETER = 3200000
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Theme: g198314poly.pat

Shape Type: Polygon

Figure 1b.
An example of a completed Arctic sea ice chart in ArcView. Note the association between polygon features in the chart and attribute data containing the WMO SIGRID ice codes.

adhering to land features), and "belts and strips" (sea ice driven into linear features by weather and ocean effects).

NIC analysts labelled ice regions falling within the boundaries of a polygon in accordance with WMO conventions (WMO, 1989). Ice concentrations, ice stages of development, and ice forms were recorded inside and around a symbol referred to as an "Egg". These "Egg Codes" summarize pertinent sea ice information in a concise form that is easily depicted and interpreted on paper charts. Egg Codes also form the basis for digitizing and exporting sea ice data as ASCII ice codes in "Sea Ice Data in Digital Form (SIGRID)" format (WMO, 1989)[6]. This is a format for transferring digital gridded fields and vector polygon data sets to Geographic Information Systems (GIS). **Figure 2** and **Table 2** provide an explanation of these ice codes.

Spatial and thematic detail and the accuracy contained in NIC sea ice charts varied from year to year depending on the observational data available, cartographic technique used, and map scale. Charts produced during the 1970s (**Figure 3**) lacked detail and often contained unverifiable estimates of ice extent and coverage. In addition, they often portrayed only the total ice concentration. Thus, early analyses were limited by:

1) The low resolution of early hardcopy satellite image "flats";
2) The shortage of *in situ* data;
3) Satellite image degradation caused by obscuring weather and ocean conditions;
4) The heavy reliance on optical imagery combined with poor solar illumination in Arctic regions.

Three technological developments occurring around 1979 allowed the inclusion of more detailed information on predominant ice stages of development, partial ice concentrations associated with each ice stage of development, and the presence of fast ice. They are:

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[6] SIGRID is sometimes referred to as "Sea Ice (Data) in Gridded Format".

1) The introduction of higher resolution visible and infrared imagery from the Advanced Very High Resolution Radiometer (AVHRR) sensor onboard the NOAA polar orbiting satellites and the Operational Linescan System (OLS) sensor onboard the Defense Meteorological Satellite Program (DMSP) satellites (Van Woert *et al*., 1992);

2) An improved understanding of ice flow shape, texture and tone evident in optical imagery related to ice stage of development and the presence of fast ice and belts and strips;

3) The increased use of theoretical ice thickness information based on environmental reports from shore stations and freezing degree-day accumulations (Zubov, 1945; Wadhams, 2000).

Analysis Techniques

Data sources, interpretation capabilities, and computer-based analysis and charting technology used to create these charts evolved considerably from 1972 through 1994, but NIC's fundamental approach to generating ice charts did not change significantly over this period. Improvements in data sources and analysis techniques manifest themselves as increased chart content and detail. **Figure 4** provides a graphical depiction of how chart detail, quantified as individual ice polygons, changed over the period of the data record.

The ice charting process began with interpretation and integration of satellite data, aerial reconnaissance data, and *in situ* observations, by analysts who were trained in remote sensing, image analysis, polar oceanography, and meteorology[7]. In most cases analysts identified areas of uniform ice concentration by subjectively estimating percent ice cover as it appeared in visible and infrared imagery. This process resulted in the production of a composite picture of ice conditions covering a period of three to five days. To capture a given week's ice conditions, analysts often integrated data acquired over a 72-hour period. This data integration process involved plotting individual reports as points on a work chart as well as analyzing sea ice boundaries (based on ice concentration, ice stage-of-development, and ice form) on top of actual satellite images, and then cartographically transferring these lines to the work chart. The analyst then added or removed lines based on the point observations, with consideration for continuity from the previous week's chart and other published climatologies (*e.g.*, U.S. Naval Oceanographic Office, 1958; Commander, Naval Oceanography Command, 1986). Analysts also made use of data older than 72 hours to estimate current ice conditions by considering prognostic output from meteorological and oceanographic numerical models run by the U.S. Navy, Fleet Numerical Meteorology and Oceanography Center, as well as U.S. National Weather Service, and foreign (*e.g*., Meteorological Service of Canada) weather services. Analysts considered forecast parameters such as air temperature, surface winds, ice drift, and ice thickness when completing a sea ice chart.

The satellite data varied widely in spatial, temporal, and radiometric resolutions (**Table 1**). The NIC used several different sources of remotely sensed data from satellites during its first 23 years (1972-1994) of ice charting in the Arctic. The sensors detected emissions in the visible, near infrared, thermal infrared and microwave portions of the electromagnetic spectrum. As a result, each instrument responded differently to the various characteristics of the sea ice or ocean surface. Even within the same satellite series, engineers made slight changes to the sensors with each successive generation of satellites (Massom, 1991). Analysts optimize their charts by capitalizing

Table 1.
Summary of remote sensing data sources used by NIC to create sea ice charts from 1972 through 1994. CSA refers to the Canadian Space Agency. For a table of other acronyms, refer to Massom (1991).

Passive Microwave Imagers

Sponsor Program	Platforms	Sensor	Lifetime	Analyzed in Digital Environment	Spectral Resolution / Sensitivity	Spatial Resolution	Susceptibility to Obscuring Weather and Ocean Conditions
DoD/NOAA/DMSP	F-8	SSM/I	1989-1990	No	19 GHz, 37 GHz	50 km (19 GHz), 35 km (37 GHz)	Moderate
DoD/NOAA/DMSP	F-9	SSM/I	1989	No	19 GHz, 37 GHz	50 km (19 GHz), 35 km (37 GHz)	Moderate
DoD/NOAA/DMSP	F-10	SSM/I	1991-1993	1993	19 GHz, 37 GHz	50 km (19 GHz), 25 km (37 GHz)	Moderate
DoD/NOAA/DMSP	F-10	SSM/I	1994	Yes	19 GHz, 37 GHz	25 km (19 GHz), 25 km (37 GHz)	Moderate
DoD/NOAA/DMSP	F-11	SSM/I	1991-1993	1993	19 GHz, 37 GHz	50 km (19 GHz), 25 km (37 GHz)	Moderate
DoD/NOAA/DMSP	F-11	SSM/I	1994	Yes	19 GHz, 37 GHz	25 km (19 GHz), 25 km (37 GHz)	Moderate
DoD/NOAA/DMSP	F-12	SSM/I	1994	Yes	19 GHz, 37 GHz	25 km (19 GHz), 25 km (37 GHz)	Moderate
NASA	NIMBUS-5	ESMR	1972-1982	No	19 GHz	25 km	Moderate
NASA	NIMBUS-7	SMMR	1978-1987	No	18 GHz, 37 GHz	50 km (18 GHz), 30 km (37 GHz)	Moderate

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[7] NIC analysts currently receive eight to twelve months of formal training in imagery interpretation, cartographic techniques, polar meteorology and oceanography, and sea ice physics.

Table 1.
(continued)

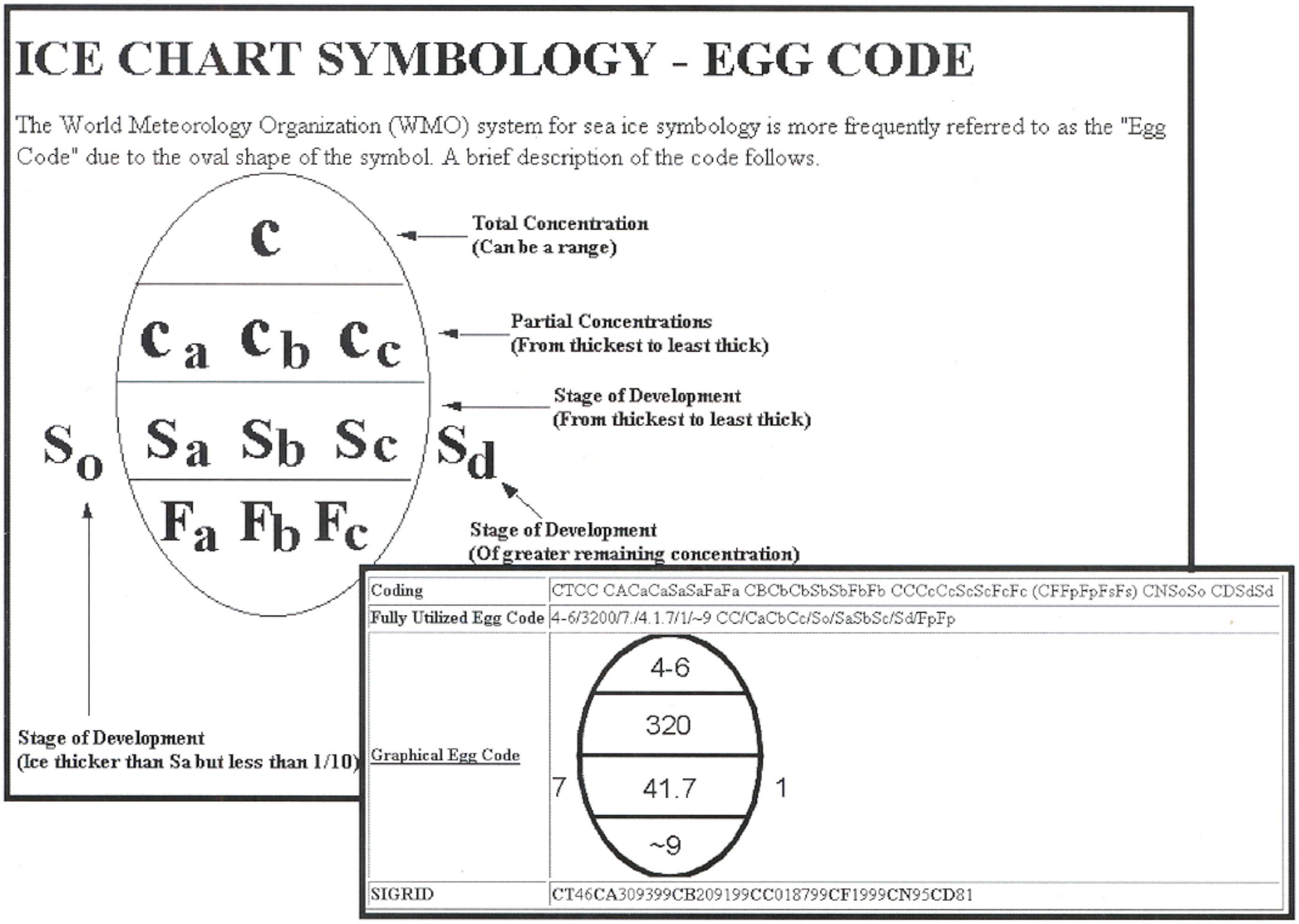
Visible and Infrared Imagers

Sponsor Program	Platforms	Sensor	Lifetime	Analyzed in Digital Environment	Spectral Resolution / Sensitivity	Spatial Resolution	Susceptibility to Obscuring Weather and Ocean Conditions
NOAA/POES/ITOS	NOAA-2	VHRR	1972-1975	No	0.6-0.7 µm (vis), 10.5-12.5 µm (IR)	1-2 km (vis), 4 km (IR)	High
NOAA/POES/ITOS	NOAA-3	VHRR	1973-1976	No	0.6-0.7 µm (vis), 10.5-12.5 µm (IR)	1-2 km (vis), 4 km (IR)	High
NOAA/POES/ITOS	NOAA-4	VHRR	1974-1978	No	0.6-0.7 µm (vis), 10.5-12.5 µm (IR)	1-2 km (vis), 4 km (IR)	High
NOAA/POES/ITOS	NOAA-5	VHRR	1976-1979	No	0.6-0.7 µm (vis), 10.5-12.5 µm (IR)	1-2 km (vis), 4 km (IR)	High
NOAA	TIROS-N	AVHRR (HRPT, LAC, GAC)	1978-1980	No	0.55-0.90 µm (vis-NIR), 10.5-11.5 µm (IR)	1-2 km (vis-NIR), 4 km (IR)	High
NOAA/POES	NOAA-6	AVHRR (HRPT, LAC, GAC)	1979-1986	No	0.55-0.68 µm (vis), 3.55-3.93 µm (NIR), 10.5-11.5 µm (IR)	1-2 km (vis), 4 km (IR)	High
NOAA/POES	NOAA-7	AVHRR (HRPT, LAC, GAC)	1981-1986	No	0.55-0.68 µm (vis), 0.73-1.10 µm (NIR), 3.55-3.93 µm (NIR), 10.3-11.3 µm (IR)	1-2 km (vis), 4 km (IR)	High
NOAA/POES	NOAA-8	AVHRR (HRPT, LAC, GAC)	1983-1986	No	0.55-0.68 µm (vis), 0.73-1.10 µm (NIR), 3.55-3.93 µm (NIR), 10.3-11.5 µm (IR)	1-2 km (vis), 4 km (IR)	High
NOAA/POES	NOAA-9	AVHRR (HRPT, LAC, GAC)	1984-1988	No	0.55-0.68 µm (vis), 0.73-1.10 µm (NIR), 10.5-11.5 µm (IR)	1-2 km (vis), 4 km (IR)	High
NOAA/POES	NOAA-10	AVHRR (HRPT, LAC, GAC)	1986-1993	1988-1993	0.55-0.68 µm (vis), 0.73-1.10 µm (NIR), 10.5-11.5 µm (IR)	1-2 km (vis), 4 km (IR)	High
NOAA/POES	NOAA-11	AVHRR (HRPT, LAC, GAC)	1988-1994	1988-1994	0.55-0.68 µm (vis), 0.73-1.10 µm (NIR), 10.5-11.5 µm (IR)	1-2 km (vis), 4 km (IR)	High
NOAA/POES	NOAA-12	AVHRR (HRPT, LAC, GAC)	1991-1994	1988-1994	0.55-0.68 µm (vis), 0.73-1.10 µm (NIR), 10.5-11.5 µm (IR)	1-2 km (vis), 4 km (IR)	High
DoD/NOAA/DMSP	F-6	OLS-Fine	1984-1987	No	0.40-1.10 µm (vis-NIR), 10.2-12.8 µm (IR)	3.7 km (vis), 4.4 km (IR)	High
DoD/NOAA/DMSP	F-7	OLS-Fine	1984-1987	No	0.40-1.10 µm (vis-NIR), 10.2-12.8 µm (IR)	3.7 km (vis), 4.4 km (IR)	High
DoD/NOAA/DMSP	F-8	OLS-Fine	1987-1989	No	0.40-1.10 µm (vis-NIR), 10.2-12.8 µm (IR)	3.7 km (vis), 4.4 km (IR)	High
DoD/NOAA/DMSP	F-8	OLS-Fine	1990	No	0.40-1.10 µm (vis-NIR), 10.2-12.8 µm (IR)	0.62 km (vis), 0.62 km (IR)	High
DoD/NOAA/DMSP	F-9	OLS-Fine	1988-1989	No	0.40-1.10 µm (vis-NIR), 10.2-12.8 µm (IR)	3.7 km (vis), 4.4 km (IR)	High
DoD/NOAA/DMSP	F-10	OLS-Fine	1991	No	0.40-1.10 µm (vis-NIR), 10.2-12.8 µm (IR)	0.62 km (vis), 0.62 km (IR)	High
DoD/NOAA/DMSP	F-11	OLS-Fine	1991	No	0.40-1.10 µm (vis-NIR), 10.2-12.8 µm (IR)	0.62 km (vis), 0.62 km (IR)	High
DoD/NOAA/DMSP	F-10	OLS-Fine	1992-1994	1993-1994	0.40-1.10 µm (vis-NIR), 10.2-12.8 µm (IR)	0.55 km (vis), 0.55 km (IR)	High
DoD/NOAA/DMSP	F-11	OLS-Fine	1992-1994	1993-1994	0.40-1.10 µm (vis-NIR), 10.2-12.8 µm (IR)	0.55 km (vis), 0.55 km (IR)	High
DoD/NOAA/DMSP	F-12	OLS-Fine	1994	Yes	0.40-1.10 µm (vis-NIR), 10.2-12.8 µm (IR)	0.55 km (vis), 0.55 km (IR)	High
USN/USCG	Aircraft	Human observer	1972-1994	No	visible	variable	Moderate

Table 1.
(continued)

Active Microwave Imagers and Altimeters							
Sponsor Program	**Platforms**	**Sensor**	**Lifetime**	**Analyzed in Digital Environment**	**Spectral Resolution / Sensitivity**	**Spatial Resolution**	**Susceptibility to Obscuring Weather and Ocean Conditions**
CSA/RSI	RADARSAT-1 *	SAR	1995-2000	Yes	C-band (5 GHz)	10 m -100 m	Low
NASA	ERS-1	SAR	1992-1994	No	C-band (5 GHz)	100 m - 240 m	Low
NASA	GEOS-3	Radar Altimeter	1975-1978	No	Ku-band (13.9 GHz)	7 km	Low
USN	GEOSAT	Radar Altimeter	1986-1989	No	Ku-band (13.5 GHz)	7 km	Low
NASA	ERS-1	Radar Altimeter	1994	No	Ku-band (13.8 GHz)	7 km	Low
USN/USCG	Aircraft	SLAR	1972-1994				Low

* Note: Included only for comparison. RADARSAT 1 data were not available prior to 1995.



ICE CHART SYMBOLOGY - EGG CODE

The World Meteorology Organization (WMO) system for sea ice symbology is more frequently referred to as the "Egg Code" due to the oval shape of the symbol. A brief description of the code follows.

Coding	CTCC CACaCaSaSaFaFa CBCbCbSbSbFbFb CCCcCcScScFcFc (CFFpFpFsFs) CNSoSo CDSdSd
Fully Utilized Egg Code	4-6/3200/7./4.1.7/1/~9 CC/CaCbCc/So/SaSbSc/Sd/FpFp
Graphical Egg Code	
SIGRID	CT46CA309399CB209199CC018799CF1999CN95CD81

Figure 2.
Breakdown of the WMO Egg Code and corresponding SIGRID code.

on the unique characteristics of each satellite sensor. These platforms and subsequent generations of sensors continue to provide data for NIC ice chart production.

Prior to 1991, NOAA routinely provided the civil, polar-orbiting, weather satellite imagery for sea ice analysis to NIC analysts on hardcopy image “flats”. The U.S. Air Force provided DMSP visible and infrared images in a similar hardcopy format. Imagery was processed using a handful of enhancement look-up tables, which greatly limited individual image interpretation. NOAA data were in fact available in digital form by 1978, and

Table 2.
Plain language and WMO SIGRID ice code elements. Information contained here was essential for the proper translation of earlier ice chart data into WMO SIGRID format. The column labeled "Egg" contains information which would appear in the WMO "Egg" labels found on international ice charts during the1980s and beyond. The SIGRID information depicted here is also essential for extraction of specific parameters for trend and variability analysis using the entire historical data set.

Concentrations (C_)

SIGRID	Plain Language	EGG
92	Totally ice-covered	10
91	Very close packed	9-10
90		9
89		8-9
81	Close to very close	8-10
80		8
79	Close packed	7-9
78		7-8
70		7
68	Open to close	6-8
67		6-7
60		6
57		5-7
56		5-6
50		5
46	Open	4-6
45		4-5
40		4
35	Very open to open	3-5
34		3-4
30		3
24		2-4
23		2-3
20		2
13	Very open	1-3
12		1-2
10		1
02	Bergy water	^
01	Open water	0-1
00	Ice free	00

DMSP data were available in digital form by 1987, but NIC had not yet developed the computer capabilities required to ingest, process, and analyze imagery in this form. By the mid-1980s, these data sources enabled analysts to provide information on "fast ice" and "belts and strips" in about 40% of the regions analyzed and information on "ice stage of development" in about 80% of the regions analyzed (**Figure 5**).

Table 2.
(continued)

Stage of Development (S)

SIGRID	Plain Language	EGG
97	Multi-year ice	9
96	Second-year ice	8
95	Old ice	7 –
93	First year, thick ice	4 –
91	First year, medium ice	1 –
87	White ice	7
86	First year ice	6
85	Grey-white ice	5
84	Grey ice	4
83	Young ice	3
82	Nilas	2
81	New, Slush, Shuga	1

Form of Ice (F_)

SIGRID	Plain Language	EGG
08	Land-fast	8
11	1/10 Belts & Strips	~1
12	2/10 Belts & Strips	~2
13	3/10 Belts & Strips	~3
14	4/10 Belts & Strips	~4
15	5/10 Belts & Strips	~5
16	6/10 Belts & Strips	~6
17	7/10 Belts & Strips	~7
18	8/10 Belts & Strips	~8
19	9/10 Belts & Strips	~9
20	10/10 Belts & Strips	~10

In 1991, NIC began to analyze satellite data using computer workstations. New procedures were required to ingest and process all available data sources in various digital formats, and these procedures were implemented gradually from 1990 through 1994. Thus, there was some "overlap" in analysis methods. During this period, analysts used both hardcopy images and newly-developed computer capabilities to generate complete Arctic sea ice charts. By providing user-defined enhancements and spatial data "overlay" functions (*e.g.*, shorelines, latitude-longitude grids, etc.), computer-based analysis allowed analysts to better discriminate the amount (or partial ice concentration) of each ice stage of development falling within a polygon, as well as the existence of ice forms like fast ice and belts and strips (see **Figure 1a**). **Figure 5** describes the aforementioned evolution of NIC ice chart content quantitatively. The authors derived these data by developing queries using ARC/INFO[8] GIS.

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[8] ARC/INFO is a registered trademark of Environmental Systems Research Institute, Inc. (ESRI), Redlands, CA, USA.

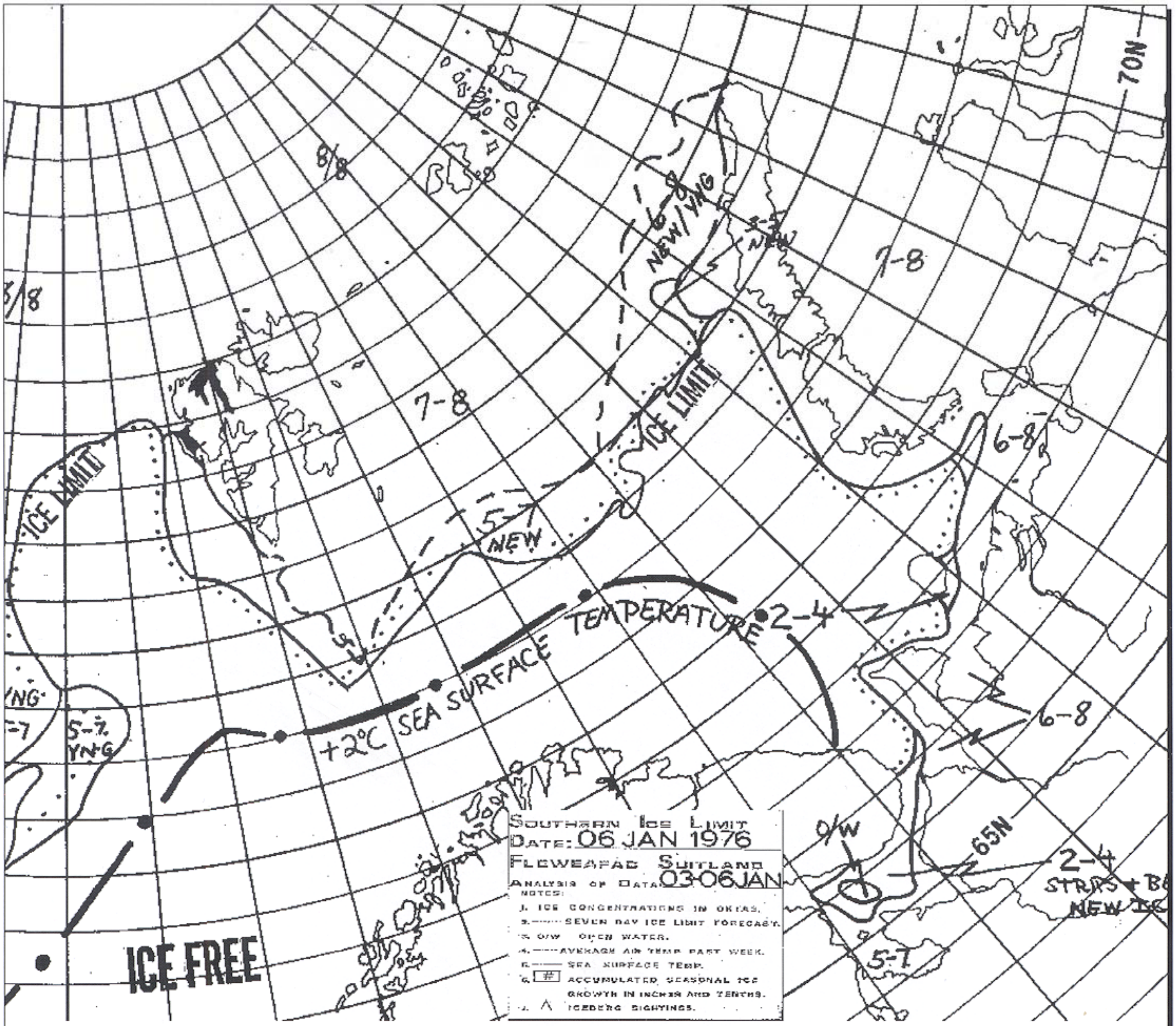

Figure 3.
An example of a 1970s NIC Sea Ice Chart. During the 1970s, NIC reported total ice concentration in octas (eighths) and used plain language to describe ice stages of development. To convert the charts into GIS data sets, NIC technicians were also required to translate these older ice codes into WMO ASCII SIGRID ice code format.

Each query was designed to search for evidence of a given ice parameter within the "icecode" field of each chart.

Beginning in the late 1970s, analysts often used data from passive microwave sensors aboard early NASA satellites, such as ESMR and SMMR, to "calibrate" their estimates of ice concentration. With the launch of the operational SSM/I in 1987, this practice was refined through the development of more reliable sea ice algorithms. Sea ice concentration reports from observers on shore, in ships, and in aircraft were often used to corroborate the ice concentrations derived from the passive microwave satellite data.

Synthetic aperture radar (SAR) data are an important source of information regarding ice type (Bertoia *et al*, 1998; Soh *et al*, 1998). However, SAR data were largely unavailable for operational use prior to 1995. For the period prior to 1995, ice stages of development were identified primarily by aircraft-, ship- or shore-based observations and theoretical ice thickness estimates based on freezing degree-day accumulations (Zubov, 1945; Wadhams, 2000). Analysts have steadily improved their understanding of how ice floe shape, distribution and texture apparent in visible and infrared imagery can serve as evidence for the determination of ice stage of development and ice form. Thus, the quality, quantity, and spatial resolution of the data have directly affected the reliability of the ice edge location, ice concentration, ice stages of development and ice form portrayed on an ice chart.

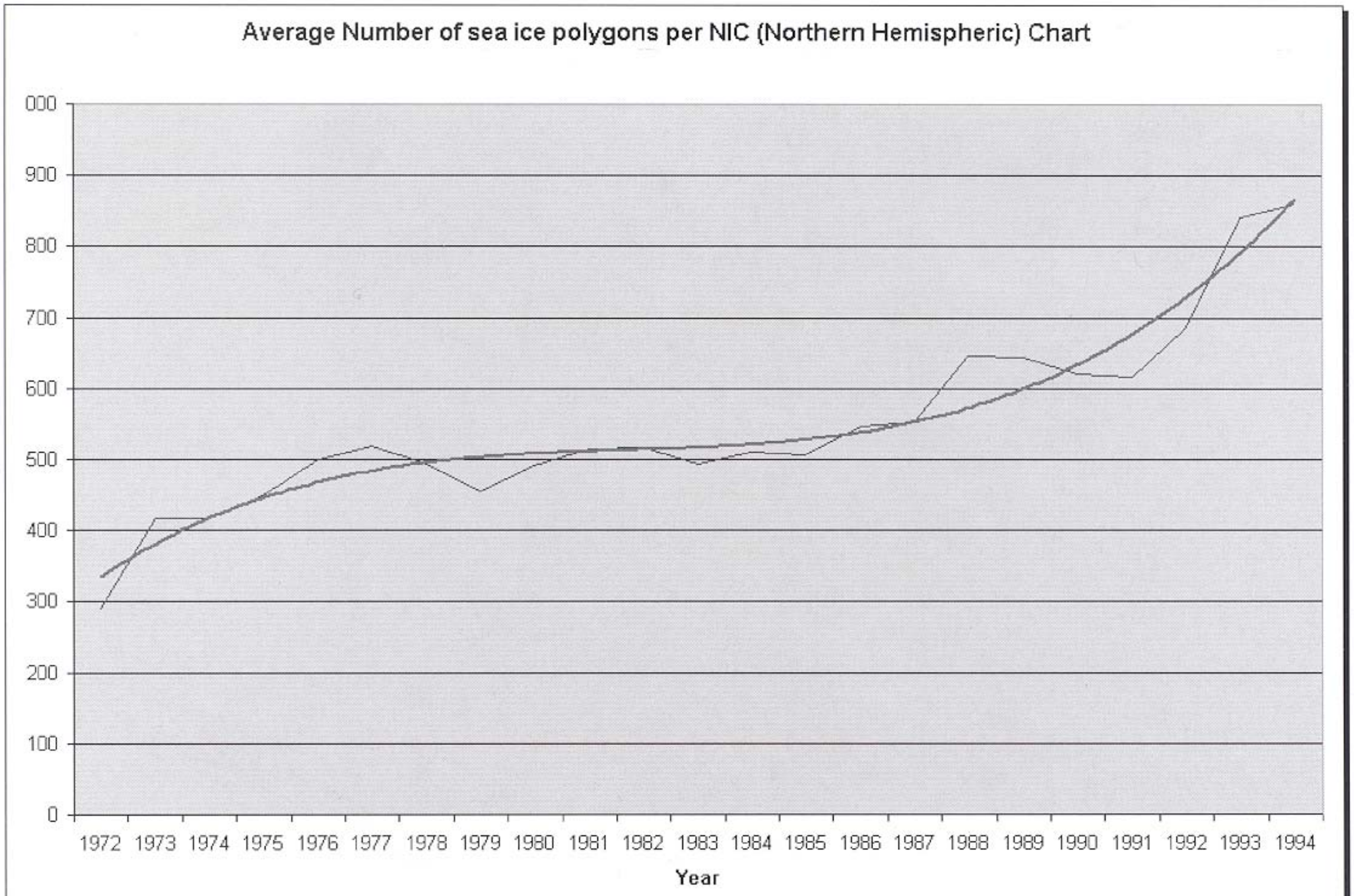

Figure 4.
Quantitative description of ice chart detail. The chart represents the average number of sea ice polygons contained in a NIC northern hemispheric ice chart for each of 23 years contained in the data set. The average number of ice polygons grew from about 300 per chart in 1972, to over 800 polygons per chart in 1994, illustrating the net effect of gradually improved data sources and analysis techniques.

As technology has advanced, so have NIC's capabilities, leading to improved definition of sea ice in the marginal ice zone. The improvement in NIC analysis capabilities has been facilitated by several factors:

1) A steady increase in the volume of incoming satellite data;
2) An improvement in the spatial resolution of data used in each analysis;
3) The ability to process and enhance remotely sensed data in digital form;
4) Passive and active microwave remote sensing capabilities which are largely insensitive to cloud cover.

New satellite technology, such as NASA's MODIS and QuikScat sensors and the Navy's Windsat/Coriolis mission should provide new contributions to the sea ice charting process.

THE ENVIRONMENTAL WORKING GROUP

In October 2000, under the auspices of the Environmental Working Group (EWG), NIC officially released its holdings of ice chart data spanning years 1972-1994. The EWG was formed in June 1995 by the U.S.-Russian Joint Commission on Economic and Technological Cooperation, which was established by U.S. Vice President Gore and Russian Prime Minister Chernomyrdin (MacDonald *et al.*, 1995). The intent of the commission was to release historical environmental data held within the national defence-related archives. Dr. James Baker, former Commerce Undersecretary for Oceans and Atmosphere and V.I. Danilov-Danilyan, former Chairman, State Committee of the Russian Federation for Environmental Protection chaired the EWG. In January 1996, the EWG Arctic Climatology Project, led by Dr. Norbert Untersteiner of the University of Washington, began compiling digital data on Arctic regions to expand scientific understanding of the Arctic. The Arctic Climatology Project ultimately developed a set of three atlases on CD-ROM focusing on Arctic oceanography, sea ice, and meteorology. These are available from the NSIDC.

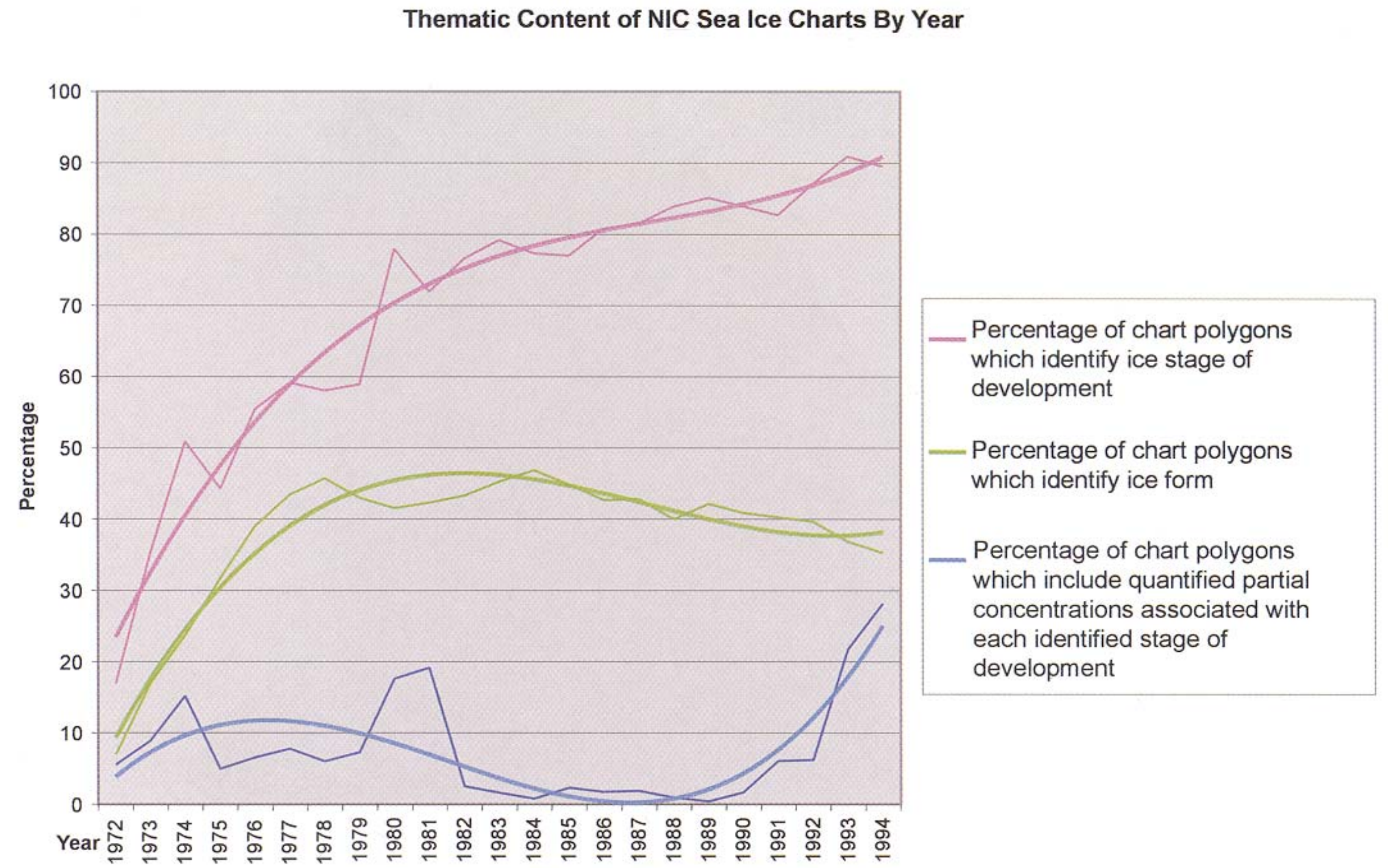

Figure 5.

Quantitative description of ice chart thematic information. The graph depicts the percentage of sea ice polygons which contain the specific information indicated. It suggests a steady increase in the ability of the charts to reveal trends in the occurrence of ice types such as multiyear or old ice. It also reveals weaknesses in the data set during earlier years, making it difficult to analyze trends in ice types prior to about 1980. The only ice parameter consistently reported over the entire data set was total concentration (CT).

The EWG Joint U.S.-Russian Arctic Sea Ice Atlas was developed by specialists from Veridian-ERIM, International, Inc., in cooperation with the NIC and the Arctic and Antarctic Research Institute (AARI) in St. Petersburg, Russia. Vice Admiral Paul Gaffney, Chief of Naval Research, led the Navy's Oceanographic community in developing its contribution to this international effort. He also provided NIC with the resources required to accomplish extensive data conversion, data quality control, and complete preparations for publishing the NIC's historical data (MacDonald *et al*, 1995).

DATA SET PRODUCTION

Scientists clearly articulated the importance of consistency and continuity in data sets such as Arctic ice coverage and extent, which are used for assessing geophysical trends. These characteristics are typically reproduced best by data sets gathered by a single sensor. However, attempts to align the end of one sensor's time series of data to that of the next generation's sensor is often difficult in practice (Vinnikov *et al*., 1999). Human analysts can also introduce inconsistencies over the period of a climatological data set, as is evident in the progressive increase in spatial and thematic detail present in the NIC sea ice charts. However, certain geophysical parameters such as ice concentration and the ice edge have been relatively consistently produced through time. The record of ice stage of development (*e.g.*, new, young, first-year, multi-year and old ice) is less complete, but has also been fairly consistently produced since approximately 1980 (**Figure 5**). Because of their complete hemispheric depiction and the incorporation of multiple data sources, NIC charts are likely to be more useful than raw satellite data or automatically classified satellite imagery for monitoring long-term climate trends.

Converting Unclassified Charts to Digital Form

NIC determined early in the EWG project that to make the ice charts suitable for environmental research the charts needed to be in a digital format and that the conversion process from paper cartographic products to digital vector or gridded data sets needed careful quality control. The majority of the ice charts from years 1972-1994 had already been made digital by 1997 through work performed at the National Climatic Data Center (NCDC) in Asheville, NC. This initial digitization resulted in an archive of ice charts in ASCII WMO SIGRID format (WMO, 1989). Lacking the computer software and hardware necessary to thoroughly review the resulting data set, NIC joined forces with the Naval Research Laboratory at Stennis Space Center (NRLSSC) to import each SIGRID data set into an ARC/INFO GIS. This process allowed NIC analysts to graphically display, query, and correct spatial and tabular data (ice codes) in an efficient manner using both ARC/INFO and ArcView GIS[9].

Converting Charts From National Security Sources to Digital Form

Also, under the plan put in place by the EWG, NIC was required to digitize a representative number of ice charts derived from National Security Sources spanning years 1972 through 1990. NIC once again began the process of converting historical paper ice charts to digital data. NIC began the process by creating standard polygon-type ice charts from the otherwise discontinuous data recorded on the original paper charts.

The general process of converting a hardcopy ice charts into a digital "geo-spatial" format consisted of several steps:

1) Registering the chart with a standard base-map of vector shoreline data in a GIS[10];
2) Digitally tracing ("digitizing") the ice polygon features from the paper chart into a new digital GIS data set (ARC/INFO "coverage");
3) Editing the resulting ice "coverage" to ensure the completeness of polygon features, particularly those which joined with the shoreline itself, and the removal of digitizing "artifacts";
4) Assigning attributes, namely ice code data, to the individual polygons during a "polygon tagging" process; and
5) The quality control, or visual inspection of the resulting digital chart using the graphical and tabular querying and visualization capabilities of ArcView GIS.

Experienced analysts reviewed, re-analyzed, and recorded meta-data (including surface air temperatures and winds) for 608 classified ice charts. The effort encompassed nineteen years of ice analysis charts that covered the Arctic marginal seas and the North Pacific. NIC selected weekly charts (representing data on or about the 15th day of each month), which would, when considered together, provide a representative depiction of typical monthly conditions in the Arctic. Analysts paid particular attention to several characteristics during the re-analysis process:

1) The validity of data sources;
2) The locations of ice concentration boundaries;
3) The completeness and closure of all analysis lines forming unique "polygons" of sea ice information;
4) The accuracy of polygon labels describing the three ice parameters: ice concentration, ice stage of development, and ice form;
5) The accuracy of ice conditions in overlap areas of any two weekly Arctic charts;
6) Continuity of ice conditions between sequential ice analysis charts.

The entire data conversion was accomplished over a two-year period through the combined efforts of NIC and NRLSSC analysts and technicians. **Figure 6** provides a simplified view of the chart digitization process. By thoroughly reviewing and converting the 23-year archive of NIC sea ice charts into digital form, NIC completed the daunting task of merging classified and unclassified ice charts into a consistent ice product useful for climate studies. **Figure 1b** displays one of NIC's digital Arctic sea ice charts in a GIS. The reader should note the "query" box, which displays the attribute table associated with each ice chart. The arrows on the graphic indicate the relationship between the spatial data (polygons) and attribute data. Of special note are the "icecode" and "CTI" attributes that characterize ice conditions within each polygon. CTI is a field derived from the "icecode" field, and indicates the total ice concentration (**Table 2**), which in **Figure 1b** is set to 68. This represents a total ice concentration of six to eight tenths in this example. The "icecode" attribute contained in the GIS coverages is crucial to the further extraction of useful sea ice parameters for climatological studies.

THE CLIMATOLOGY: STATISTICS AND VARIABILITY

High Resolution Climatology Data

Directed by the EWG to release climatological statistics from its 19-year archive of ice charts derived from National Security Sources, NIC devised a simple routine written in Arc Macro Language (AML)[11] to extract the "total concentration" (CT) value from each polygon of a given ice chart. NIC then converted the GIS coverages (polygon data) to binary gridded fields (ARC/INFO GRID format) and created grids based on this total concentration value. The output grid cell size is 12,500 metres, in a polar stereographic projection with central meridian located at 180 degrees east/west and latitude of true scale located at 60 degrees north. NIC also created total ice concentration gridded fields from the unclassified weekly ice chart data. NIC then merged these two data sets from classified and unclassified sources, to generate a complete hemispheric gridded field for each month. The resulting merged grids enabled NIC to use ARC/INFO's GRID module to compute gridded fields containing two statistics:

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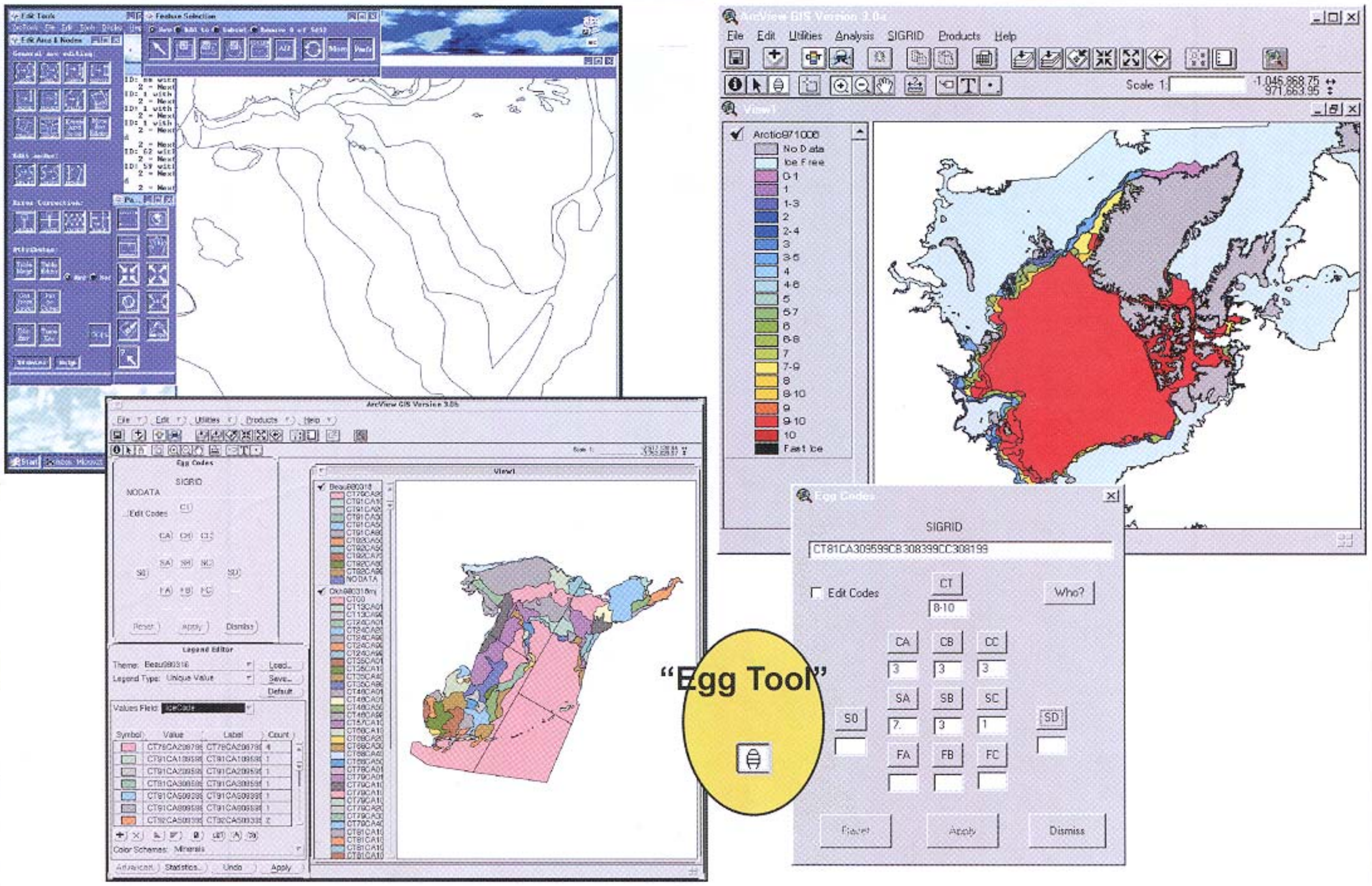
[9] ArcView is a registered trademark of the Environmental Systems Research Institute, Inc. (ESRI), Redlands, CA, USA.

[10] Resulting spatial accuracy largely depended on the condition of the original paper chart and the consistency of the chart's shoreline with the digital shoreline (Doody *et al*., 1998).

[11] AML was developed for use in ARC/INFO GIS by ESRI, Inc., Redlands, CA, USA.



SIGRID: CT81CA309599CB308399CC308199

CT: 8-10

CA: 3 CB: 3 CC: 3

SA: 7 SB: 3 SC: 1

Figure 6.
The ice chart digitization process in a nutshell. Counter-clockwise from upper left, digitization of spatial data (polygons) using ARC/INFO, followed by polygon attribution using ArcView, resulting in a complete hemispheric "Coverage" (process often required several smaller charts to be "mapjoined" by a technician using ARC/INFO).

1) Monthly median total ice concentration fields (**Figure 7a**);
2) The number of occurrences of any sea ice over the 19-year period (**Figure 7b**).

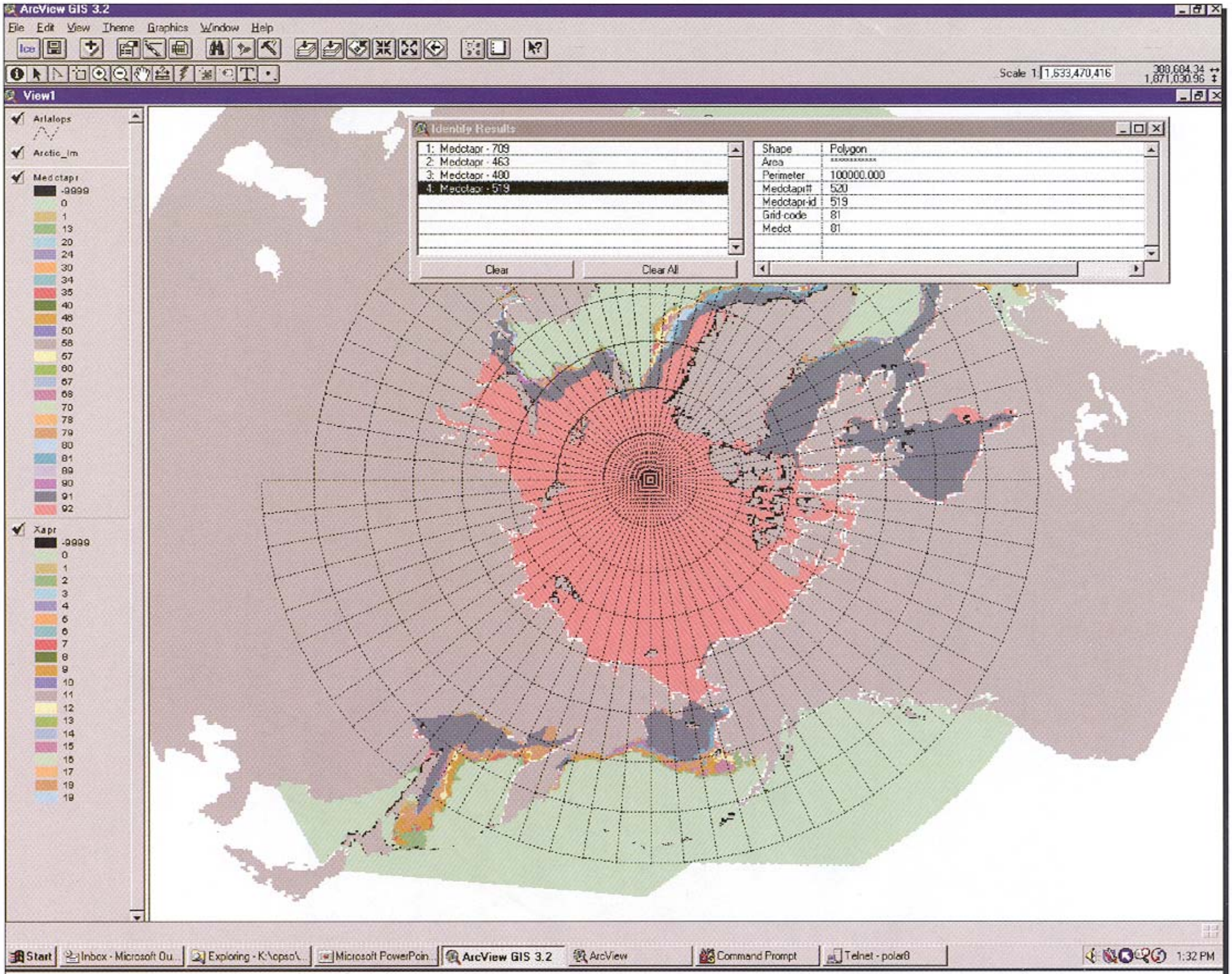
The median total ice concentration was obtained by computing the median value for a given grid cell over all available grids for a given month (*i.e.*, half the data in the 19-value sample fall on or above this median value and half fall on or below this value). The "total ice occurrence" statistic is an enumeration of years for a given month that ice of any concentration occurred in a given grid cell (the total number of years is 19). The possible values for this output grid are integer values ranging from 0 through 19.

NIC quality-controlled and revised the resulting climatology grids by smoothing areas into a contoured product. This was done by deleting or joining small sea ice areas at the ice edge or within the ice field itself and then merging them with surrounding attributes. The objective of the smoothing was to create continuous regions of sea ice concentration and ice occurrence to more accurately depict the ice edge, the marginal ice zone, and the concentrated ice pack. NIC also revised the fast ice category using other climatological data (*e.g.*, U.S. Naval Oceanographic Office, 1958; Commander, Naval Oceanography Command, 1986) to ensure seasonal continuity. NIC conducted two separate reviews of the resulting climatology data by comparing the products with weekly ice analyses and to the individual classified data products.

The resulting gridded fields of median concentration provide a starting point for researchers interested in understanding typical ice conditions in the Arctic for a given month. The frequency of ice occurrence at each grid location helps reveal common and unusual sea ice extents, and may prove useful to researchers interested in sea ice variability or trend studies.

Arctic Sea Ice Variability Observed from NIC Data

A relatively small number of dedicated scientists has attempted to compile extensive Arctic sea ice data sets in a "piecemeal" fashion, incorporating information from operational ice charts and a variety of international sources, in hopes of characterizing variability in sea ice over time-scales sufficient to capture changes in climate (Walsh, 1978; Walsh and Johnson, 1979; Kelly, 1979, to name a few). These studies are crucial in the assessment of recent historical conditions in the Arctic. Much of the data resulting from these studies have been published through the NSIDC in the form of monthly Arctic sea ice concentration records (1901 to 1995), digitized to a standard



1: Medctapr - 709
2: Medctapr - 463
3: Medctapr - 480
4: Medctapr - 519

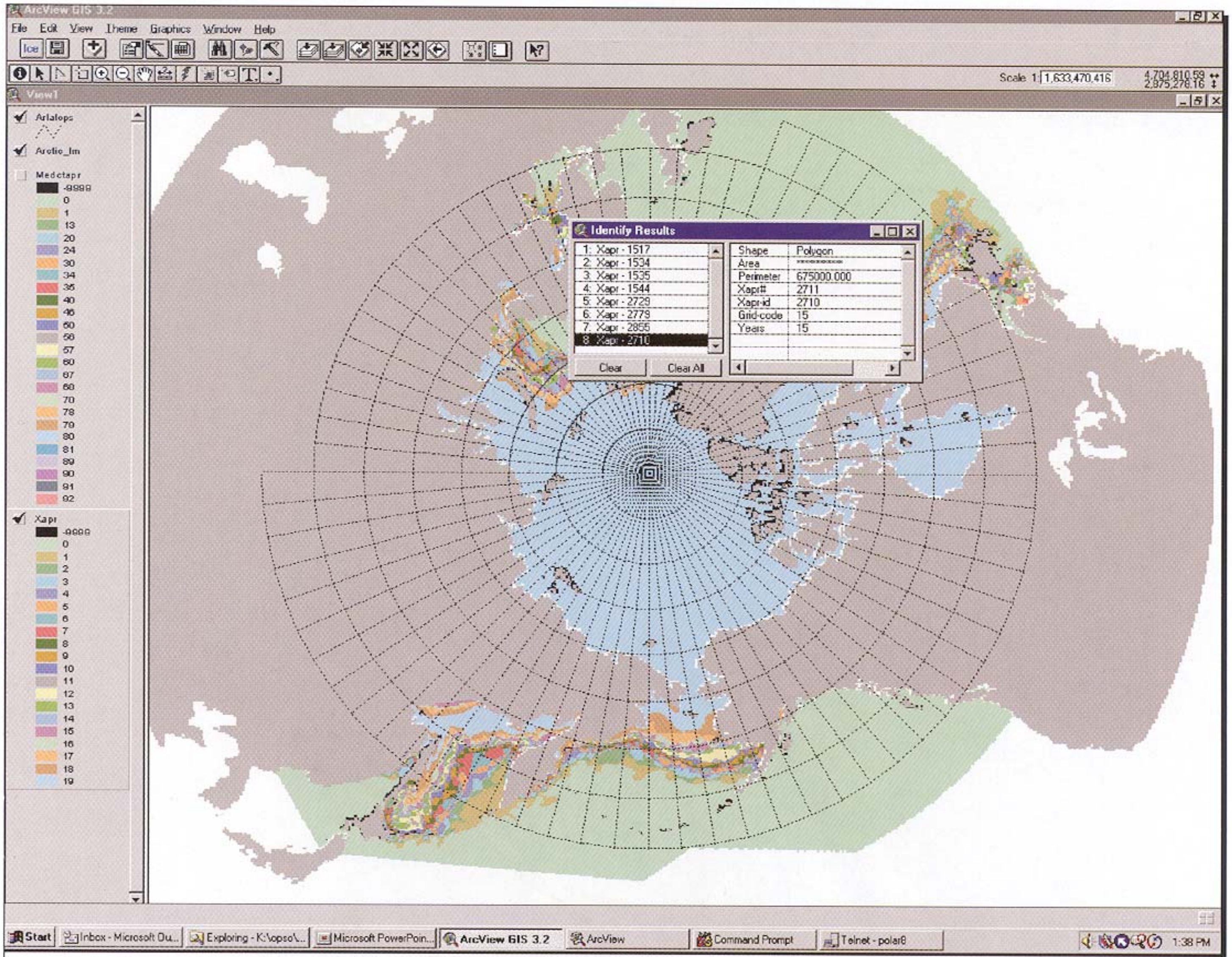
Shape	Polygon
Area	***********
Perimeter	100000.000
Medctapr#	520
Medctapr-id	519
Grid-code	81
Medct	81

Figure 7a.
EWG Climatology Grid. This grid represents the median sea ice concentration for April. It was computed by generating grids based on total concentration (CT) from representative charts for April of years 1972-1990, then computing the median value for all 19 years.

one-degree grid (cylindrical projection), with the aim of providing a "relatively uniform set of sea ice extent for all longitudes, as a basis for hemispheric scale studies of observed sea ice fluctuations" (Walsh 1978). These studies were recently augmented by analyses derived from the satellite passive microwave record, whose duration is now long enough to reveal climate trends (Cavalieri *et al*., 1997). With the advent of the NIC digital Arctic sea ice data set, the quality of information available for the late twentieth century is greatly improved. Moreover, NSIDC intends to incorporate the NIC data set into its 1-degree gridded data for years 1901-1995. This record should significantly enhance our understanding of twentieth century Arctic sea ice conditions and will be available for all those interested in climate (Walsh, personal communication, 2001). The NIC data set is indeed an important resource in its own right, and can be used on its own to provide important new insight into twentieth century Arctic sea ice conditions.

Even in the form of simple maps, the NIC data demonstrate great potential for increasing our understanding of sea ice variability in the Arctic (**Figure 8**). Colour composite images based on the NIC data for April (**Figure 8a**) and September (**Figure 8b**) portray mean ice concentration for 1972-1978 in blue, mean ice concentration for 1979-85 in green, and mean ice concentration for 1986-92 in red. Thus identical, coincident mean ice concentrations for each of the three periods yield shades of gray (including black and white) in the composite images. Differences in mean ice concentration among the three periods yield varying shades of red, green, blue, yellow and cyan. Thus, colourful portions of the images in fact reveal significant changes in Arctic ice concentration from one period to the next. **Table 3** shows how the colours should be interpreted.

Displayed in this manner, the data demonstrate highly non-uniform changes in ice concentration over the North Polar Region from 1972 through 1992, and reflect large-scale



1: Xapr - 1517
2: Xapr - 1534
3: Xapr - 1535
4: Xapr - 1544
5: Xapr - 2729
6: Xapr - 2779
7: Xapr - 2855
8: Xapr - 2710

Shape	Polygon
Area	**********
Perimeter	675000.000
Xapr#	2711
Xapr-id	2710
Grid-code	15
Years	15

Figure 7b.
EWG Climatology Grid. This grid represents the number of years in which sea ice occurred in April, and was computed using one representative ice chart from the middle of April in each year from 1972 through 1990.

changes in atmospheric and oceanographic conditions. The record indicates that ice concentration changes cannot be adequately described as a simple, Arctic-wide trend, as increased and decreased ice concentrations are more apparent in some regions (and some periods) than in others. The data also illustrate extensive regions where no change is discernible, including the high Arctic (white) and the extremities of the marginal ice zone (black). In both cases, the absence of ice concentration changes in these areas relates mostly to the data set's insensitivity to ice concentration differences when the absolute ice concentrations are either very high or very low.

Some of the observed variability relates to known influences such as the North Atlantic Oscillation (NAO). The NAO is a large-scale fluctuation in atmospheric mass between the Icelandic low-pressure region and the Azores high-pressure region (Stephenson, 1999). **Figure 9** portrays the data organized into two periods characterized by distinctly different NAO indices. The earlier period (1977-1980, in blue) represents years during which there existed a (mildly) negative NAO Index (strongly negative NAO years preceded the period of the NIC data set). The more recent period (1990-1994, in green) represents years during which existed a strongly positive NAO Index (Dickson *et al.*, 2000). Thus, in **Figure 9**, areas containing pure blue tones indicate a negative correlation between NAO index and ice concentration, whereas areas of pure green indicate a positive correlation between NAO index and ice concentration. Regions with cyan tones (an equal contribution of blue and green) indicate no change.

Figures 8 and **9** suggest that, in the Barents Sea, the main mode of variability relates to the NAO index. The index has a very strong influence on the strength of the Norwegian Current and, during the late 1980s and early 1990s, caused warm Atlantic water (the main conveyor of heat into the Arctic Ocean) to extend 20% further into the Arctic than normal. Venegas and Mysak (2000) suggest a 9-10 year periodicity in sea level pressure and sea ice extent in association with this

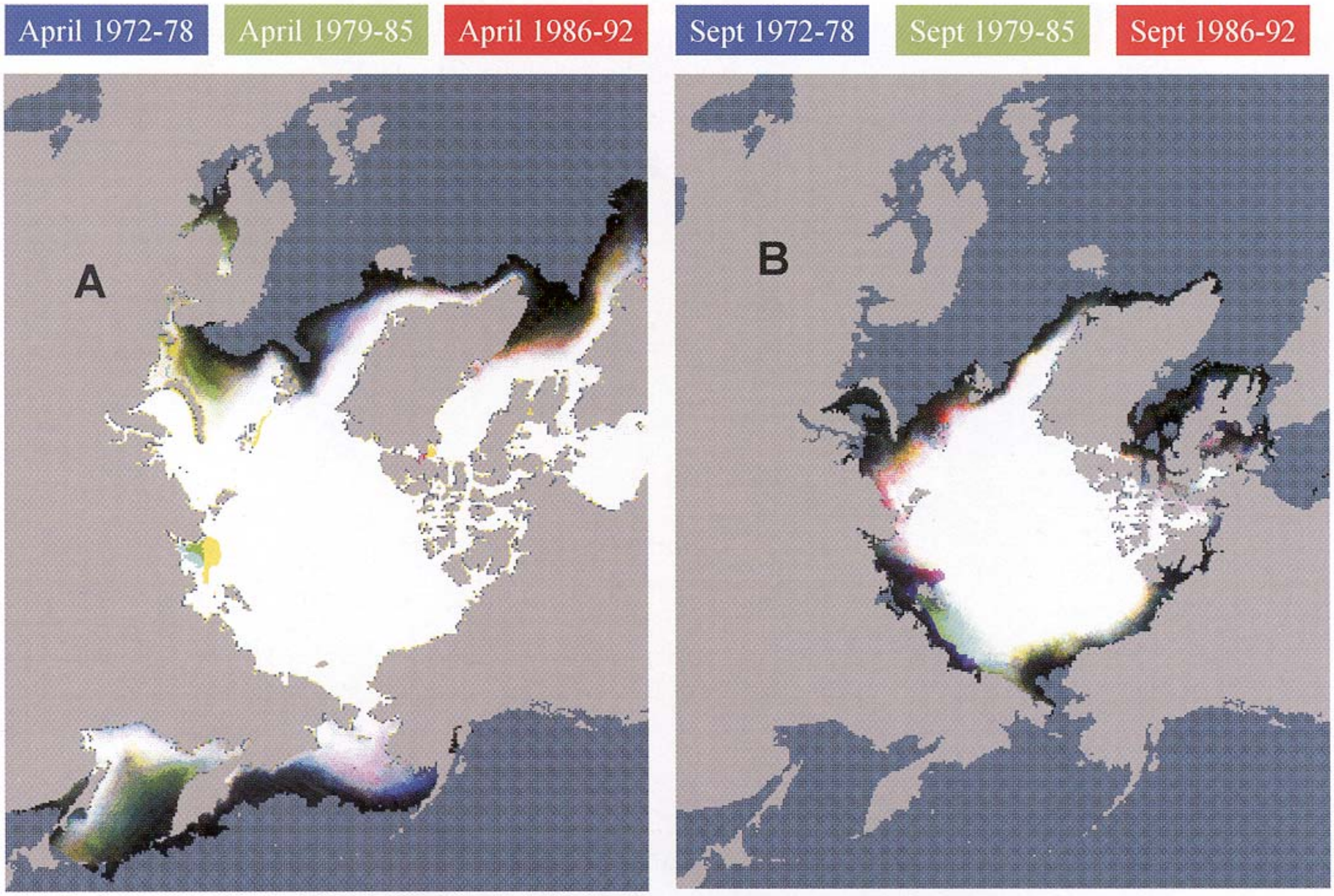


Figure 8.
Colour composite change detection images based on 21 years of total ice concentration data extracted from the NIC historical data set. Gray shades (including black and white) indicate areas of no change in ice concentration from 1972 through 1992. Colouration differences indicate non-uniform changes in ice coverage over this same period.

Table 3.
Colour legend for Figure 8. The colour seen in the image indicates the relative contributions from each period's average ice concentration. The brighter a colour is in Figure 8, the higher the absolute ice concentration during the corresponding period. Colour contribution estimates of "low" and "high" in this table are relative, intended as guidance for interpreting the colours as they pertain to mean ice concentration during each period.

Map colour	1972-78 (Blue)	1979-85 (Green)	1986-92 (Red)
White / gray / black	Identical concentrations for all periods (black=low; white=high)		
Red	Low	Low	High
Green	Low	High	Low
Blue	High	Low	Low
Yellow	Low	High	High
Cyan	High	High	Low
Magenta	High	Low	High

phenomenon. The extent of the influence of the NAO on the ice edge position in winter is clear from **Figures 8** and **9**.

Figures 8a and **9a** suggest that the most notable change in the Greenland Sea has been during winter, and is accompanied by the retreat of the Odden during the later years of the record. The Labrador Sea behaves in a see-saw (dipole-like) manner with the Greenland Sea. Here, there is also a clear link with the NAO index, but in this case positive NAO years are associated with heavier ice conditions (**Figure 9**). The ocean surface under these conditions is cooled by stronger than normal northerly winds, with accompanying sea ice formation.

Figure 8b shows a particularly strong reduction in the summer ice coverage in the East Siberian Sea between the 1979-85 and the 1986-92 periods. The change actually occurred during 1988-89, when the typically strong and broad Arctic high pressure system weakened and shrank, at the same time moving towards the Alaskan coast. The weakening resulted in less ice moving across the Arctic into the East Siberian sector. Furthermore, the ice thickness distribution in the East Siberian sector became thinner as the source of thick ice was curtailed. With less thick ice being imported into the region, the most obvious effect on ice coverage is at the end of summer as there is less surviving ice and more open water (**Figure 8b**).

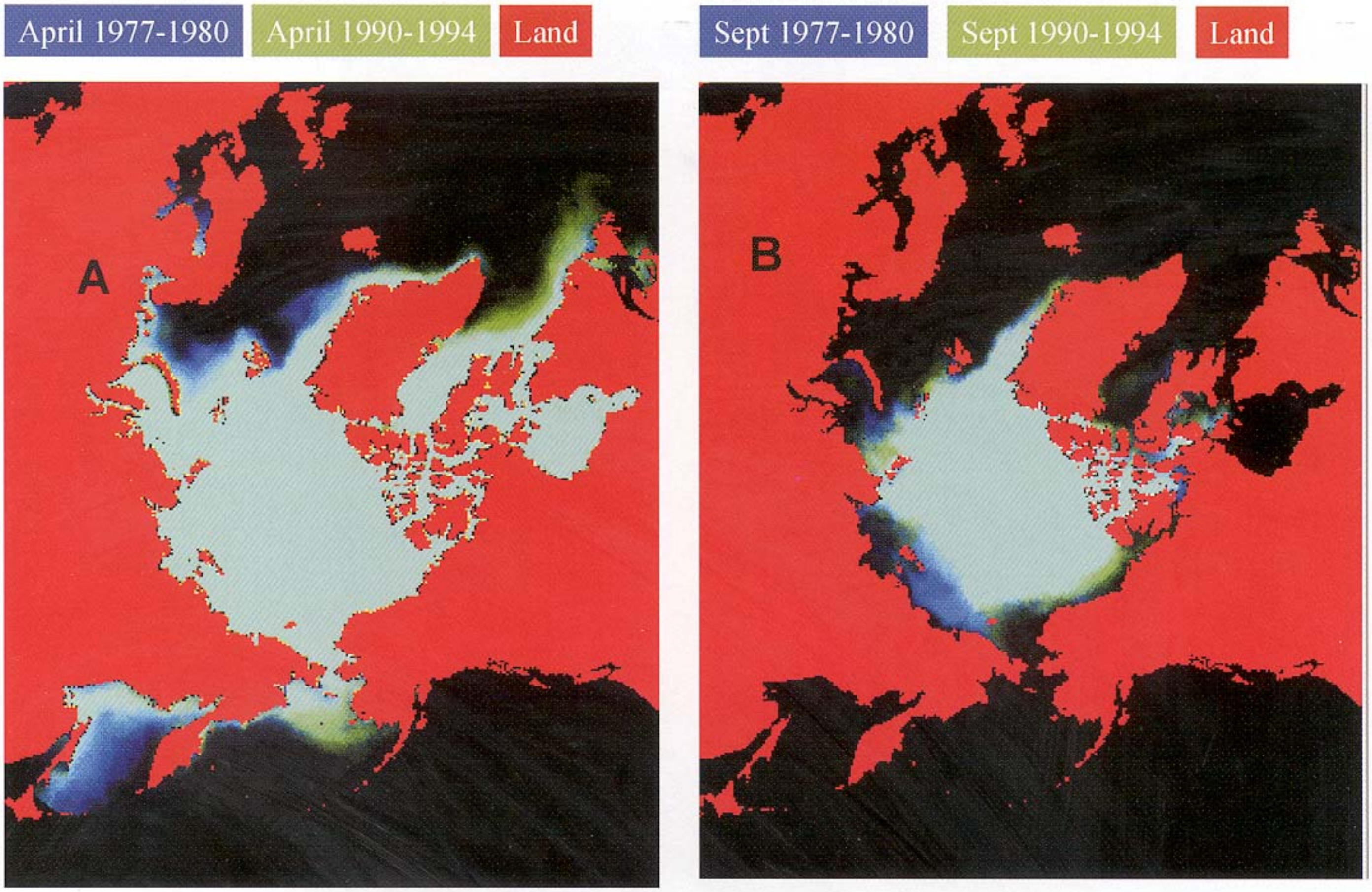


Figure 9.
Colour Composite of Mean Ice Concentration Data for two periods, including Negative NAO Index Years (blue) and Positive NAO Index Years (green). Equal contributions of blue and green create the cyan areas across much of the Arctic, indicating no change in ice concentration between the two periods.

Over the period of the NIC data set, the Sea of Okhotsk ice coverage appears to have had an opposite pattern of variability to the Bering Sea. During a period of a strongly positive NAO index, onshore wind anomalies reduce the advection of ice offshore, allowing new ice to form in the coastal polynya (Dickson *et al.*, 2000). The changes in the Pacific sector of the sub-Arctic have been as distinct during winter as those of the Barents Sea (**Figure 9a**); yet have not received as much attention from the scientific community.

These figures demonstrate two simple ways in which the NIC data set can be exploited to reveal patterns of sea ice concentration variability across the Arctic and to begin the process of identifying causes of observed changes. Computing simple statistics and examining the data in the manner discussed here constitute only the most basic illustration of results which may be obtained from the NIC 23-year digital ice chart archive and associated high-resolution climatology data.

LIMITATIONS OF THE DATA SET

As discussed earlier, the NIC digital sea ice charts were created using many different sources of remotely sensed and *in situ* data over the course of 23 years. Moreover, NIC sea ice charts represent the work of many analysts over the years, none of whom produced sea ice analyses in exactly the same manner. In the 1970s and early 1980s data resolution, processing, and delivery limitations resulted in ice charts which recorded very little detail pertaining to ice concentration and ice types. In early years, in the absence of near real-time data with large-area coverage, analysts often resorted to interpretation of simple climatological maps (*e.g.*, U. S. Naval Oceanographic Office, 1958; Commander, Naval Oceanography Command, 1986) to fill in gaps between observed data in weekly charts. Thus, particularly during the earlier part of the period, significant areas of the data represent interpolations or perceived climatological conditions.

One of the real limitations of the data set is that it is not possible to distinguish, except subjectively, between these areas and those which are based on reliable primary data. Users of the data will also recognize that there is no specific reference to data sources inherent in the ice charts. In the future, NIC is expected to make further use of GIS technology, to enable the storage of geographically referenced attributes related to data sources, such as satellite sensors and dates of original data acquisition.

Personal computing and satellite sensor advances of the late-1980s and early 1990s gave NIC an increasing ability to capture more detail in an admittedly more complex ice chart. These inherent complexities were multiplied by the manifold process of converting the charts to digital spatial data for ultimate analysis in a computational environment.

One recognized shortfall of the 23-year northern hemispheric data set is the arbitrary exclusion of ice south of 45-degrees north latitude. In some years, sea ice may extend south of 45-degrees north latitude into the waters south of Newfoundland, the Sea of Okhotsk, the Yellow Sea, and the Sea of Japan. Weekly maps of sea ice in the Yellow Sea were analyzed and digitized in 1998, and are expected to be published separately.

An additional limitation is that sea ice chart generation is carried out by a manual form of data fusion, which is inevitably subject to error on the parts of analysts and cartographic technicians. About three man-years have been devoted to removing obvious errors (for example, ensuring consistency in ice parameters across cartographic boundaries). However, some errors surely remain and there is not sufficient information to allow historical analyses to be truly validated.

SUMMARY

Through the auspices of the U.S.-Russian Joint Commission on Economic and Technology Cooperation, the National Ice Center developed a Arctic sea ice climatology for the period 1972 through 1994. This climatological data set along with the weekly ice charts that form the basis for the climatology were recently released to the scientific community and are available from the NIC and the NSIDC.

The mission of the National Ice Center is to provide the best possible operational sea ice analyses to its customers. The weekly products that are produced at the National Ice Center are based on *in situ* observations as well as a data from a constantly evolving suite of space borne sensors. Given this mandate and the constant changes in technology, the weekly charts have steadily improved both in resolution and fidelity over the years. While this improvement is important for operational users, it can potentially introduce trends or biases into the product. Thus, users of this data set should be cognizant of this issue.

In spite of limitations, the data set holds enormous untapped potential for environmental and climate research. Here we have illustrated the importance of this data set by examining the relationship between sea ice extent represented by the NIC data set and the North Atlantic Oscillation. Consistent with the findings of previous studies, sea ice conditions in the Barents sea region were found to be strongly linked to variations in the North Atlantic Oscillation. In addition, strong variations in the Pacific Sector of the Arctic were found to vary in relation to the phase of the North Atlantic Oscillation.

Thus, the NIC historical data set provides a superb general picture of the Arctic sea ice conditions. It is anticipated that NIC will continue an extensive quality control process on its digital ice charts for years 1995 and beyond, with subsequent publication of these data.

ACKNOWLEDGEMENTS

Special thanks go to all of the NIC sea ice analysts and production team members, throughout the years. They, after all, created this incredible data set, week by week, over 23 years. These dedicated professionals continue to produce a wealth of sea ice charts even today. Additional thanks go to Martin Doody, John Breckenridge, Gary McKay (all affiliated with Naval Research Laboratory, Stennis Space Center during the creation of the NIC EWG data set) and Ralph Perniciaro (Planning Systems, Inc., Slidell, LA) whose talent and dedication to geographic information systems technology made the conversion of NIC's data to digital form possible. We also extend a hearty thanks to Mr. Don Barnett, Mr. Frank Kniskern and Mr. Jeff Andrews, whose many years of experience in sea ice analysis were absolutely essential in the creation and quality control of this data set. Finally, thanks to VADM Paul Gaffney, USN, former Chief of Naval Research, and the Office of Naval Research for the financial support for this project.

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