U.S. Department of Commerce
National Ocean and Atmospheric Administration
National Weather Service
National Centers for Environmental Prediction

Technical Note

Automated Passive Microwave Sea Ice Concentration Analysis At NCEP

Robert W. Grumbine
Ocean Modelling Branch

March 1996

This is an unreviewed manuscript, primarily intended for informal exchange of information among the NCEP staff members.

OMB contribution 120

Abstract

Gridded sea ice concentration fields are required for sea ice forecast model initialization, as well as supporting a number of other National Centers for Environmental Prediction (NCEP) and outside interests. An automated processing scheme, which has been run in developmental mode daily since May 1, 1994, is described herein. The resulting fields are suitable for further manual operational ice concentration analysis, and have been used for that purpose by the National Ice Center since February, 1995. These fields are also used for starting the sea ice forecast model. The analysis fields are also used to create global grids for making ice/no ice determinations, and has been used for that purpose by the NCEP/NCAR Climate Reanalysis Project.

1 Introduction

Sea ice extent, concentration, and thickness are important factors governing the safety of shipping and geophysical exploration in polar latitudes. Sea ice also provides an important boundary condition for weather forecasting, climate modelling, sea surface temperature analysis, and wave height and direction analysis and forecasting. The sea ice cover is a dynamic feature which profoundly affects the state of the ocean-atmosphere system, and responds quickly to changes in weather or ocean conditions. All of these applications require accurate analyses of the present condition of the ice cover. This report details the data flow and processing used in an automated analysis procedure.

The Special Sensor Microwave Imager (SSMI) instrument on the Defense Meteorological Satellite Program (DMSP) series is a passive microwave instrument that has the capability of providing sea ice concentrations. This is the first sensor/technique used at NCEP for an automated sea ice analysis. Other techniques which can be considered are the active microwave (scatterometer, synthetic aperture radar), passive infrared, and passive visible. Passive microwave is developed first because it has the longest history, it is an all-weather technique (unlike visible and infrared, which can be seriously affected by the presence of clouds), it is an all-year technique (unlike visible, which is useless during polar night), and provides nearly complete polar coverage on a daily basis (unlike all other sensors – active microwave currently means the ERS-1, which has a 500 km swath width, versus the 1400 km of the SSMI).

The algorithm used to derive ice concentrations from satellite observations is the NASA-Team [Cavalieri, 1992] algorithm. There are many algorithms possible, and several others exist. This one is chosen for the initial implementation because it is the best documented, best verified versus ground truth, has the longest history, and has been preferred for operational use by the National Ice Center (NIC) [David Helms, personal communication, 1995].

The sea ice data grids constructed by the procedures described here are used by the NCEP (National Centers for Environmental Prediction) ice model and the Climate Data Assimilation System, and are suitable for use by other groups as well. The procedure is not strictly a satellite observation process as the sensor technique can be misled into diagnosing ice where there is none. The procedure for removing false ice is detailed in section 5, and relies on sea surface temperature information.

Expected audiences for this document and the data files produced by the methods to be described are: programmers who might need to modify the codes described herein, sea ice analysts who will be producing official ice analyses including information from the other platforms, sea ice forecasters, sea ice modellers who want to obtain model initial conditions, other modellers who want to obtain a sea ice boundary condition, and climatologists. This document traces the route of the data, section 2 describes the platform, the sensor, and the production of the initial satellite data file. Section 3 describes the quality control performed on the brightness temperatures. Section 4 describes the computation of the ice concentration and production of a sea ice concentration grid. The method of filtering spurious ice concentrations from these grids is detailed in section 5. Finally, the production of global sea ice grids in GRIB format, and their locations on the NCEP computer system is given in section 6. Ice concentrations for historic purposes are described in section 7.

2 Data Source

Sea ice concentration grids are being constructed from the special sensor microwave / imager (SSMI), which orbits on the DMSP (Defense Meteorological Satellite Program) F-13. The DMSP F-13 satellite is the replacement to the F-11, and its characteristics with respect to orbit and electronics are identical. The DMSP F-10 SSMI sensor is not used because the NASA Team algorithm has not been calibrated for it. The decision to calibrate the algorithm only for F-11 (F-13) was made because the orbit for F-10 is more eccentric than originally planned, the data would overlap the F-11 (thereby being redundant), and the Navy had selected F-11 as the platform of choice for performing sea ice analyses [Don Cavalieri, personal communication]. The DMSP F-11 satellite is a polar orbiter, with a swath width of 1400 km, and maximum observed latitude of 87.6 [Goodberlet and Swift, 1992]. The orbital period is approximately 102 minutes, giving approximately 14.1 orbits per day.

The SSMI sensor is a total power radiometer, operating at vertical and horizontal polarizations at 19.35, 37.0 and 85.5 GHz, and vertical polarization only at 22.2 GHz [Goodberlet and Swift, 1992]. The same antenna is used for all frequencies, giving resolution (half-power beam width) varying from 69 by 43 km (cross-scan, along-scan) at 19.35 GHz, to 15 by 13 km at 85.5 GHz. Resolution at 37 GHz is 37 by 28 km. [Goodberlet and Swift, 1992]. The fundamental quantity observed is the total power received by the radiometer. This can be translated uniquely to an antenna temperature (the temperature at which a black body would emit the same energy as measured by the radiometer. This must be distinguished from the brightness temperature, as the antenna temperature is affected by antenna sensitivity and the brightness temperature isn't.), and it is this which is saved in the data files which are transmitted to the shared processing network. Data are received from the DMSP F-13 by FNMOC (Fleet Numerical Meteorology and Oceanography Center). The data are processed into SDR (Satellite Data Record) [Akunuri et al., 1993] format by NESDIS (National Environmental Satellite Data Information Service) and transmitted across the shared processor network to the NCEP.

Users of the SDR data file must be aware that the data flow path is not perfect. Most relevant to the sea ice problem is that not every orbit reaches the operational 30 orbit file on the front end. For a typical day, note that although 30 consecutive orbits span only 2.25 days, the actual span is closer to 3.5. The 30 orbits which are present occupy approximately 170 Mb.

3 Brightness Temperatures

For constructing the brightness temperature grids a 12 hour window, before and after 00 UTC of the current day, is currently used. The time of the ascending node of the orbit must lie within that window. The data begin shortly after the ascending node time. The brightness temperature extraction program (ssmi) is currently scheduled to run at 8:30, Eastern Local Time (daylight or standard, which ever is in effect), giving a UTC run time of 12:30 during daylight time, and 13:30 during standard time. As there is some delay between scan and distribution of data, this time will miss the most recent orbit or two, even without there being a skipped orbit. It is routine, however, to have 12 orbits of the possible 14 in the analysis.

It is common to have bad data on a scan line. Typically, this means unphysical antenna temperatures (Ta), locations off the planet (latitude greater than 90), or an impossible surface type. The surface types are encoded into an 8 bit byte. Valid surface types are in the range 0-7 [Marie Colton, personal communication]. Surface types greater than 7 occur routinely (several hundred times per 30-orbit file). Surface codes greater than 7 are always associated with bad brightness temperatures (values outside the range in table 1), so that surface type is checked prior to brightness temperatures. If a bad surface type is encountered, the entire scan line is treated as bad data.

Note that the values actually encoded in the SDR file are antenna temperatures. The brightness temperatures are computed by correcting for the beam pattern [Hollinger, 1989]. Because there may be alternate methods developed in the future for making the beam pattern correction, it is the antenna temperatures which are saved. A function 'antenna' has been written whose sole purpose is to make the antenna to brightness temperature conversion.

Based on Gloersen et al. [1994], figure 2.3.2., a range of plausible brightness temperatures has been established, and is given in table 1. If any brightness temperature on a scan line lies outside the ranges given in table 1, the entire scan line is treated as bad data, and thrown out. As a matter of practice, this is almost redundant in that bad Ta values seldom occur alone. Typically the entire scan line is bad, or the entire line is good.

Table 1. Brightness temperature data ranges as a function of frequency and polarization.

ν	Max	Min	ν	Max	Min
19 H	295	75	19 V	295	150
22 V	295	150			
37 H	295	100	37 V	295	150
85 H	295	125	85 V	295	125

Although the orbit file does include a surface type encoded into the data record, the surface type is not a constant at the resolution of the analysis grid. This means that a given point on the 25 km analysis grid can be 'land' 2 days, but 'water' the third. Because of the differing land masks which different users may have, no land masking is performed internally to the processing. A cosmetic land mask is applied to the native grid and the latitude longitude grid for display fields only.

The land mask now used was derived from the NESDIS high resolution land tags file [W. Pichel, personal communication, 1995]. The basic data are a land/no land flag, on a 1/16th degree latitude-longitude. If any land was detectable within 5 km of the cell center, the point was flagged as land in this grid. For generating the ice model land mask, each point in the land tags was remapped to the nearest point on the basic 25.4 km grid cell and a cumulative count was kept of the land versus no-land decisions. If more than half of the flags were 'land', the point is set to land in the sea ice mask. If one quarter to one half of the points were land, the ice mask is coast. If fewer than one quarter of the points were land, the ice mask is for water. This definition is inclined to declare points at which there will be land contamination to be water (and therefore compute ice concentrations which have that contamination). This definition is used at the request of the National Ice Center and the Anchorage Forecast Office, which have the expertise and need to extract ice information near the shore.

4 Computing and Gridding Ice Concentrations

The antenna temperatures are remapped from the scan points onto a 25.4 km, true at 60, polar stereographic grid oriented to 80 W in the northern hemisphere, and 100 E in the southern hemisphere. The northern hemisphere grid is 385x465 pixels, with the pole at 191, 231. The southern hemisphere grid is 345x355 pixels with the pole at 151, 181. The grid points are numbered from 1 to N, which follows the standard Fortran usage. For use in C programs, the pole point needs to be shifted 1 less in both i and j. The convention for raster output is that 1,1 is the lower left corner. The earth model used is the Hughes Ellipsoid with radius 6378.273E3 meters, and e^2 of 0.006693883. Hughes is the contractor for the satellite, so this keeps the mapping/ unmapping mutually consistent. Antenna temperatures are mapped over all points without regard to the surface type. This permits *post hoc* application of land masks which may be different than that derived above.

The sea ice concentration is computed by the NASA-Team ice concentration algorithm [Cavlieri, 1992], with the improved weather filter [Gloersen and Cavalieri, 1986], and using the F-8 referenced brightness temperatures [Abdalati et al., 1995], after the data have been converted to brightness temperatures [Hollinger, 1989]. The weather filter typically removes about 12,000 points on the 179,025 point northern hemisphere grid.

The above weather filter is extended for NCEP use. While the pixel size is 25.4 km, the sensor spot size is about twice that at 19 GHz (a frequency used in the filter). The extension is to consider adjacent pairs of points with respect to the weather filter. If the filter would reject a point having the average character of the pair, then both points in the pair are rejected as weather. This rejects an additional several hundred to couple of thousand points, without often affecting the ice pack analysis.

The weather filter, both in its original application and in the extended version used at NCEP can be triggered even within the ice pack. This was an unexpected discovery, prior study suggested that the weather filter would not be triggered within the ice pack. The experimental version of the algorithm implementation set ice concentrations to zero when the weather filter was triggered. Although the false filtering occurs seldom, only at a few points on a given day, and only every couple of days, ice concentrations are no longer reset to zero. Instead, a flag is put in to the data record noting that the point was a weather point.

If more than one observation is made on a pixel (possible due to multiple orbits, particularly in high latitudes) the concentrations for each pass are averaged. This is in contrast to the common usage, which is to compute the averaged brightness temperatures and then derive an ice concentration from them. Computing the ice concentration first and then averaging is used because the algorithm is not linear, and the weather filter can remove contamination from a single observation which would not be apparent after brightness temperatures were averaged. The discrepancies between the two methods are small in practice, with bias about 0.2%, and about 0.65% standard deviation.

The poles are not observed by the satellite. In the southern hemisphere this is not a concern for sea ice mapping, as there is no sea near the pole there. In the northern hemisphere, it is necessary to fill in the polar gap. The method used is to fill in the disk of missing data according to a Laplacean with boundary values specified by the observations. This solution is taken on two grounds. First, it gives the minimum gradient fill pattern. Second, it is observed that the Laplacean of the ice concentrations is small in regions away from the ice edge, which the polar data void always is.

Ice concentrations are computed from the NASA-Team algorithm without applying a concentration cap. Typically ice concentrations over 100% are reset to 100. The limit is physically correct of course. For conducting manual ice analyses, however, the over 100% ice concentrations may carry information about the ice pack state. For the derived latitude-longitude grid, the concentrations are capped at 100%. Ice concentrations do not exceed 128% even in the uncapped mode. Above 128, there are flags denoting different surface and data conditions: Land is 157, Bad data is 166, Weather is 177, Coast is 195, and No data is 224.

5 Final Filtering

Even after applying the brightness temperature-derived weather filter, there are still points falsely reported as containing some ice. Since we have other information, such as the sea surface temperatures (SST), we apply this knowledge to remove as many spurious points as possible. This procedure was used for the ECMWF climate reanalysis [Nomura, 1993]. In this method, if the SST was analyzed to be greater than 2 °C, the ice concentration was reset to zero. This method is good as long as low concentrations are not being considered important. In the reanalysis and for weather prediction purposes, an ice/no ice decision is desired. For a cut off decision like that a value of around 50% is used (reanalysis uses 55%). So the algorithm is suitable for its intended use. The operational 1 degree OISST [Reynolds and Smith, 1994] is used for filtering in producing the global latitude longitude ice grid.

The quality of the ice edge analysis itself (typically unaffected by weather and wave contamination in the algorithm) has been examined by the National Ice Center [David Helms, personal communication]. They find, by comparison to AVHRR imagery which is considered (by the human analyst) to be cloud free, that the passive microwave maps created by the above technique are typically accurate to the resolution of the microwave maps. The NIC is using OLS imagery, with approximately 0.6 km resolution. Where available, this is the preferred human analysis tool. In order to verify that no false ice points are being passed through, an IDL-based animation tool was made. False ice points are readily distinguishable by the fact that they 'flicker' in and out of the animation.

This product can be used by people and groups who are knowledgeable about sea ice and do not use automated ingestion of sea ice maps expecting to have every grid point filled with data.

6 Sea Ice Maps

For groups which are not sea ice experts, or which require a filled grid ice map, additional processing is required. The satellite takes about 3 days to ensure coverage of all pixels. The present method is to construct a map wherein the most recent day's observation is retained for each pixel. This is done only on the latitude-longitude grid.

6.1 Creating a Grib Map

Many external users (Reanalysis, MRF, NESDIS high resolution SST analysis) use a latitude-longitude grid for their operations. So ice concentrations are created on that grid (a half-degree latitude- longitude grid) by locating the point on the native grid closest to the lat-long grid and assigning its value to the lat-long grid.

The 0.5 degree latitude-longitude map is written out in GRIB format, and occupies approximately 225 Kb disk memory. Routine 'mkllglob' based on H. Juang program GRIBIT [H. Juang, personal communication] performs the remapping and encoding. Two polar sterographic GRIB maps (the native grid, in which unobserved points are not filled in) are also created, one for each hemisphere, on the native analysis and processing grid, again from programs (psgrib.north, psgrib.south) derived from H. Juang's GRIBIT.

6.2 Data Availability

Analyses are on line for up to one month. Table 2 gives machine name, present IP number, and directory. File names are in the form type.yymmdd, where yymmdd is the 6 digit date, and the types are defined by table 3:

Table 2: Ice concentration data availability

Machine	IP number	directory
cray3	140.90.57.22	/dm/wd21rg/ssmi/fifteenth
cray4	140.90.56.24	/marine/ice/ice.analy
polar	140.90.192.85	pub/

Table 3: Output file type definitions

Type	Description
eng	Engribbed half degree latitude-longitude ice concentration file
b3north	Character binary grid for the northern hemisphere
b3south	Character binary grid for the southern hemisphere
northpsg	Engribbed northern hemisphere ice concentrations
southpsg	Engribbed southern hemisphere ice concentrations
n3ssmi	Northern native binary antenna temperature and ice concentrations
s3ssmi	Southern native binary antenna temperature and ice concentrations

The machine polar is set up for anonymous ftp and for WWW service. The URL for WWW service is http://polar.wwb.noaa.gov/seaice/. Anonymous ftp service is through ftp://polar.wwb.noaa.gov/pub/ice. Cray3 and cray4 require you to have an account on the machine. Data are typically available by 9:30 ET on all three machines. The n3ssmi and s3ssmi files can be read by program getfld.

7 Historic Ice Concentrations

Passive microwave satellites have been orbiting continuously since late October, 1978. The sequence has been Nimbus-7 SMMR, DMSP F-8, DMSP F-11, DMSP F-13. Data transmission periods are given in the following table:

Name	Dates
SMMR	10/25/78 to 8/20/87
F-8	7/9/87 to 12/31/91
F-11	12/3/91 to 5/16/95 for reanalysis (still producing data)
F-13	5/16/95 to future

The DMSP series was designed to have the same electronics, making their measurements directly comparable. In practice, there was some difference between the F-8 and F-11, requiring a regression (already described) to maintain data continuity and compatibility [Abdalati, W., et al., 1995].

The F-11 to F-13 antenna temperature intercomparison is still in progress since both satellites are collecting data. A preliminary analysis of the derived ice concentrations for the period of overlap in the southern hemisphere (winter hemisphere is preferred for antenna temperature intercomparison [Abdalati, W. et al., 1995]) is summarized in table 4. The final figures are the straight line regression between F11 ice concentration and F-13 ice concentrations (F-11 concentration = a0 + a1* F-13 concentration). There were a total of 1,432,060 matched points between the two sensors. The resulting mean concentrations do differ from each other, but by a negligible amount relative to the algorithm accuracy. The regression lines are quite near to zero correction, and again, the difference is physically negligible. Therefore, although an antenna temperature re-calibration should be performed, the effects can be expected to be negligible to any use which does not require greater than 2-3 %

accuracy in ice concentrations.

Table 4: Regression of F-11 derived ice concentrations on F-13 derived ice concentrations.

Month	r^2	F-11 mean	F-13 mean	a_0	a_1
May	0.987	69.972	69.348	0.531	1.001
June	0.989	74.612	73.620	1.264	0.996
July	0.987	78.953	78.680	-0.001	1.003
August	0.986	80.436	79.989	0.466	1.000
September	0.984	77.999	77.424	0.807	0.997
Total	0.986	78.086	77.588	0.555	0.999

7.1 NCEP/NCAR Reanalysis Project

Sea ice concentration fields to the nearest percent have been produced by A. Nomura [1993] (10/25/78 to 12/2/91) and R. Grumbine (this document) (12/3/91 to present) for the reanalysis project. For 1/1/95 to the present, the analyses are based on the automated algorithm described in this report. For the period 12/3/91 to 12/31/94, the brightness temperature data used by Grumbine are from the US National Snow and Ice Data Center. The algorithm is as described in section 5. For the period 10/25/78 to 12/2/91, the ice data were ice concentrations produced by the the US National Snow and Ice Data Center. For both the Nomura period and Grumbine through 12/31/94, the SST's used are the reanalysis SST's. The reanalysis ice concentration data, on a 1x1 degree grid, are available on request to R. Grumbine. The December 1991 to December 1994 data are available at URL <ftp://polar.wwb.noaa.gov/pub/reanl91t94> in compressed format. Data for 1995 are available in <ftp://polar.wwb.noaa.gov/pub/cdas>. From October 31, 1995 onward the grids are half degree.

7.2 ISLSCP I

The International Satellite Land Surface Climatology Project, Initiative I (ISLSCP I) includes sea ice data for 1987 and 1988. The data are monthly averages of ice concentration derived by R. Grumbine from A. Nomura's analyses for the climate reanalysis project. Nomura's analyses relied on ice concentrations from the US National Snow and Ice Data Center. The monthly data are available on the ISLSCP I CD set, or as a uuencoded, compressed, tar file, by anonymous ftp to polar.wwb.noaa.gov, in directory pub/islscp1.

8 Conclusions

The analysis method described herein has already been found to be useful for both daily operations (NIC ice analyses) and for climate considerations (ISLSCP I and

Reanalysis). The method does still have a weakness in that spurious ice from the passive microwave algorithm still requires reference to non-passive microwave data sources.

In the future, we expect to take that weakness and make a strength out of it. Data required to compute ice growth rates is already available. This can be developed to provide a more physical constraint on ice growth implied by the passive microwave observations. Work is already in progress on variational data assimilation based on the passive microwave data and sea ice modelling. The resulting product is expected to reduce the problem of data gaps and false satellite reports of ice, in that the physical processes for the ice cover are reasonably well known. As an offshoot of that project, it should also be possible to reconstruct the ice thickness – a quantity which is not directly observable by satellite.

The NASA Team ice concentration algorithm was used for this project. This is not the only algorithm possible, but, as already noted, was the algorithm with the best documentation and longest history. Other algorithms are becoming public and are getting better documented, so that a future project will be an algorithm intercomparison.

The source codes used for this work are available on request. Some codes may be available from the WWW home page.

9 Acknowledgements

Several people and groups have been involved in examining the results of the analysis procedure described here or in providing technical support. I would like to thank A. Nomura for providing his analysis codes, M. Colten of FNMOC for discussions regarding the data in the SDR files and the data flow, G. Legg, J. Cornelius, and P. Chang regarding SSMI data flow, R. Kistler and S. Saha who examined the data for suitability in climate reanalysis, R. Weaver, C. Hanson, V. Troisi, and N. Sandoval of the NSIDC who were most helpful in resolving early apparent discrepancies between my processing of the historic brightness temperatures and theirs, M. Sullivan, C. Bertoia, T. Rush of the NIC for feedback on the usefullness of the native ice concentration grids, D. Helms, then of the NIC, for establishing the data link which permitted the data to reach the NIC and for feedback on the utility of the files, B. Katz and N. Grody for assistance with the antenna to brightness temperature conversion meaning and practice, and D. Cavalieri for many discussions regarding the algorithm, the sensor, and providing code for implementing the algorithm, D. Cavalieri.

I would like to thank D. B. Rao, V. M. Haliburton, and D. Cavalieri for their editorial assistance in preparing the final version of this document.

10 Appendix: Acronyms

DMSP	Defense Meteorological Sattelite Program
EMC	Environmental Modelling Center
EOS	Earth Observing System
ERS	European Remote Sensing Satellite
FNMOC	Fleet Numerical Meteorology and Oceanography Center
GRIB	Gridded Binary – WMO standard for exchange of gridded fields
HDF	Hierarchal Data format – EOS standard for exchange of gridded fields
MRF	Medium Range Forecast
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NESDIS	National Environmental Satellite Data Information Service
NIC	National Ice Center
NSIDC	National Snow and Ice Data Center
OMB	Ocean Modelling Branch
SDR	Satellite Data Record
SMMR	Scanning Multichannel Microwave Radiometer
SSMI	Special Sensor Microwave/ Imager
SST	Sea surface temperature
WMO	World Meteorological Organization

References

Abdalati, W., K. Steffen, C. Otto and K. C. Jezek Comparison of brightness temperatures from SSMI instruments on the DMSP F8 and F11 satellites for Antarctica and the Greenland ice sheet *Int. J. Rem. Sensing*, **16**, 1223-1229, 1995.

Akunuri, R., J. Pritchard, L. Dennis Orbit-by-Orbit Microwave Derived Products (SDR) Interface Control Documentation Hughes STX Corporation 1993.

Cavalieri, D. J. Sea ice algorithm in NASA Sea Ice Validation Program for the Defense Meteorological Satellite Program Special Sensor Microwave Imager: Final Report NASA Technical Memorandum 104559, pp. 25-32, 1992.

Gloersen, P., W. Campbell, D. Cavalieri, J. Comiso, C. Parkinson, and H. Zwally Arctic and Antarctic sea ice, 1978-1987: Satellite passive microwave observations and analysis NASA SP-511 (Greenbelt, MD, NASA), 1994.

Gloersen, P. and D. J. Cavalieri Reduction of weather effects in the calculation of sea ice concentration from microwave radiances it J. Geophys. Res., **91**, 3913-3919, 1986.

Goodberlet, M. and C. T. Swift DMSP SSM/I Sensor Description and Calibration in NASA Sea Ice Validation Program for the Defense Meteorological Satellite Program Special Sensor Microwave Imager: Final Report NASA Technical Memorandum 104559, pp. 5-20, 1992.

Hollinger, J., Special Sensor Microwave/Imager Calibration/Validation, Naval Research Labs, Washington, DC, 1989.

Nomura, A. Sea surface temperature and sea ice data for the ECMWF Re-analysis (ERA) system ECMWF Re-analysis project Report number 2, 1993.

Reynolds, R. W. and T. W. Smith, Improved global sea surface temperature analysis using optimal interpolation, *J. Climate*, **7**, 949-964, 1994.