THE 2002 GREAT LAKES WINTER EXPERIMENT (GLAWEX 2002)
THREE-DIMENSIONAL MAPPING OF THE GREAT LAKES ICE COVER

G. A. Leshkevich[1] and S. V. Nghiem[2]

[1]Great Lakes Environmental Research Laboratory
National Oceanic and Atmospheric Administration
Ann Arbor, Michigan 48105
Tel: 734-741-2265, Fax: 734-741-2055
E-mail: leshkevich@glerl.noaa.gov

[2]Jet Propulsion Laboratory, 300-235
California Institute of Technology
4800 Oak Grove, Pasadena, CA 91101
Tel: 818-354-2982, Fax: 818-393-3077
E-mail: nghiem@solar.jpl.nasa.gov

Introduction

In his recommendations for Great Lakes ice research, [*Marshall*, 1966] concludes that "studies are needed to classify Great Lakes ice types, their distribution and drift during the winter, and the subtle changes in albedo and imagery which mark the gradual disintegration of the ice and the imminent breakup." Early investigations by various researchers were conducted to classify and categorize ice types and features [*Chase*, 1972; *Bryan*, 1975], to map ice distribution [*McMillan and Forsyth*, 1976; *Leshkevich*, 1976], and to monitor and attempt to forecast ice movement with remotely sensed data [*Strong*, 1973; *McGinnis and Schneider*, 1978; *Rumer et al.*,1979; *Schneider et al.*, 1981]. Most of the early research on Great Lakes ice cover was done by visual interpretation of satellite and other remotely sensed data [*Rondy*, 1971; *Schertler et al.*, 1975; *Wartha*, 1977]. Because of the size and extent of the Great Lakes and the variety of ice types found there, the timely and objective qualities inherent in computer processing of satellite data make it well suited for such studies. Moreover, the all-weather, day/night sensing capabilities of Synthetic Aperture Radar (SAR) make it well suited to the short daylight, cloud dominated winter conditions in the Great Lakes region.

Background

Much of the satellite ice interpretation algorithm development in the Great Lakes region began during the Extension to the Navigation Season Demonstration Study conducted during the 1970's. However, many of the early studies were done by visual interpretation of satellite and other remotely sensed data. Starting in the mid-1970's, a series of studies including field studies and computer digital image processing, explored techniques and algorithms to classify and map freshwater ice cover using LANDSAT, NOAA/AVHRR, ERS-1/2, and RADARSAT SAR data [*Leshkevich*, 1985; *Leshkevich, et al.*,1990; 1997, 2000; *Nghiem et al.*, 1998]. The goal of much of this work is to develop an automated or semi-automated method to classify and map Great Lakes ice cover using satellite digital imagery. All single-polarization SAR applications to Great

Lakes ice have been for areal mapping, and measurement of ice thickness using interferometric SAR has not been investigated.

Objective

The objective of the GLAWEX 2002 experiment is to map the Great Lakes ice cover in three dimensions including ice area, ice type, and ice thickness for scientific and operational applications. The method is to use polarimetric and interferometric SAR together with field observations and in-situ measurements. Results are to be applied to satellite multipolar/polarimetric SARs such as ENVISAT, RADARSAT-2, ALOS, and other future SAR in the long term, and to determine design parameters and use of future interferometric SAR.

Results from this experiment and their applications to long-term SAR data help to address several science topics including ice mass and marine water level change, climate change, ecosystem change and its environmental and biological effects. We also discuss consequences of these changes and the use of ice information in resource management, hazard prediction and mitigation, and operational and industrial applications.

Science Issues

Ice Mass And Marine Water Level Change

In the world's largest freshwater surface covering an area of 245,000 km^2 with a drainage basin extending 1110 km north-south and 1390 km east-west [*Goetz*, Ed., 1990], ice in the Great Lakes is the most obvious seasonal transformation that results in tremendous variations in the regional ice mass formation and decay. Both ice cover and ice thickness are necessary to determine ice mass balance in lakes. Changes in lake ice mass directly affect hydrologic mass balance and marine water level. Furthermore, ice volume on the Great Lakes governs heat fluxes and thus interactions between lake, atmosphere, and land such as lake-effect snow. Such effect can result in anomalous snow accumulation on land as evident this year in the Buffalo, New York region where several feet of snow fell within a few days. The record snowfall of the 1978-1979 snow season was 32.5 feet (feet not inches) in Keweenaw County, Michigan. In the Lake Erie snowbelt, severe winter weather has a major impact on traffic flow maintenance on interstate highways and on public safety in general [*Schmidlin*, 1993]. Lake ice mechanical strength strongly depends on ice thickness, which is very important to navigation hazard and the shipping industry.

Marine water level in the Great Lakes can be significantly affected by the ice jam mechanism. A naturally formed ice arch, which prevents ice transport into a river, as a natural ice control structure is investigated in *Port Huron Ice Control Model Studies* [*Calkins et al.*, 1982]. Large masses of thick ice can break the ice arch, causing ice jams, and creating winter flooding. A particularly susceptible area is the St. Clair River where ice imported from southern Lake Huron can create large ice jams on the river. A record ice jam occurred in 1984 over a period of 24 days.

A loss of $1.7 million (more than $3 million/day in today's value) per day in shipping loss was reported and it would take at least 3 years for the marine water levels in Lakes St. Clair and Erie to return to pre-jam conditions [*Derecki and Quinn*, 1986]. Thus, ice jams change river discharge and water flow, which can have an impact on hydropower operation and generation. Ice jam hazard conditions can be predicted if ice concentration is known. A study has found that the ice passage can be forecast based on the mean surface ice concentration, which correlates to the presence or absence of the ice arch corresponding to 9.5% and 27.3% ice concentration, respectively [*Daly*, 1992].

Expected Results

We expect the following results:

a. Polarimetric and interferometric SAR signatures of ice types in the Great Lakes together with ice geophysical characteristics
b. Development and verification of polarimetric and interferometric algorithms for three-dimensional ice mapping over the Great Lakes
c. Multi-parameter polarimetric and interferometric images of Great Lakes ice
d. Trends in marine water level associated with ice mass change in the long term

The value of the results in the short term is to determine and map ice mass balance over the Great Lakes. The approach is to use the relationship between polarimentric and interferometric SAR signatures with ice geophysical characteristics (layer, density, thickness,…) determined from the field experiment to develop and validate ice mass algorithm, then the algorithm is applied to SAR data to obtain ice mass mapping over large areas.

We expect results of ice mass mapping are to be used to understand and determine the relationship between spatial distribution of ice mass and ice jam mechanisms, such as how the natural ice arc is formed and is destroyed, and how ice mass contributes to the severity of ice jams causing marine water level change in the Great Lakes. In the long term, we expect results on ice mass change and marine water level change to be used to address their consequences on water cycle (lake-effect snow) and regional climate (surface energy balance) due to lake-ice-atmosphere interactions.

Trends in marine water level associated with ice mass change in the long term can be used to address science issues related to lake-ice-atmosphere interactions. Assuming a static and close system, ice mass and water level are balanced because of the floating ice. However, variations in Great Lakes ice mass and distribution have significant impact on marine water level because of their effects on regional water cycle through atmospheric interactions. Furthermore, catastrophic events such as ice jams can disrupt water flow and discharge causing significant change in water level. The cause of such events depends on ice concentration distribution and ice mass as indicated above.

Climate Change

On one hand, the Great Lakes can be significantly affected by climate change and thus serve as a very sensitive integrated indicator for climate monitoring. On the other hand, the Great Lakes significantly affects regional climate and thus contributes to global climate variability. The interactions between the Great Lakes and climate have impact on Great Lakes ice cover and thickness (or ice mass overall), which in turn affects the regional geophysical and meteorological characteristics and thus feedback to climate change. We discuss the science issues and expected results in the following paragraphs.

Global climate change can have a significant impact on the Great Lakes. Because of the unique geolocation, Great Lakes ice cover can be changed dramatically. This is because the polar jet stream can form an entirely zonal pattern (subtype W3 of atmospheric circulation) effectively blocking an advection of cold Arctic air to the south, or a more meridional pattern (type C1 of atmospheric circulation) causing cold winters over the Great Lakes [*Rodionov and Assel*, 2001]. Information on the ice cover and transport provides quantitative, sensitive, and early indicators to understand regional and global climate change. A number of studies were commissioned to study climate change effects on the lakes [*Smith*, 1991]. Ice cover duration is predicted, by several General Circulation Models (GCMs), to be reduced by 5 to 13 weeks under the CO_2 (carbon dioxide) doubling scenario [*Assel*, 1991]. Such a change is dramatic with respect to the relatively short time of the current seasonal ice cover duration. Observations of ice seasons on the Great Lakes show an earlier ice departure indicating a trend toward earlier and warmer springs in the upper Midwest [*Hanson et al*., 1992]. Freezeup and breakup dates represent integrated climatic conditions during the winter-spring period when most warming is forecast to occur; this timing provides an early indication of climatic warming [*Assel and Robertson*, 1995].

The Great Lakes have significant effects on the regional climate and can be considered as an important component in the global climate system. Studies of Great Lakes effects on regional and large-scale climate [*Lofgren*, 1997] show that the lakes (1) alter the meridional air temperature gradient leading to an intensification and displacement of the polar jet stream, (2) cause a phase shift in the annual cycle of latent and sensible heat flux, and (3) increase annual water vapor flux convergence. On regional and synoptic scales, the Great Lakes aggregate circulation splits a synoptic-scale high into two distinct centers and redirects and intensifies a weak synoptic-scale low, as verified by existing observations [*Sousounis and Fritsch*, 1994]. Model simulations also reveal that the developing lake-aggregate circulation influences significantly the lake shore surface winds, and that a secondary dynamic response appears at a distant location, adjacent to the eastern seaboard, suggesting that the lakes may play a direct role in some cases of East Coast cyclogenesis [*Sousounis and Fritsch*, 1994]. It is noted that the regional and meso-scale circulation is affected by lake interactions and lake thermodynamic processes are seasonally influenced by ice cover and ice thickness in the Great Lakes.

Expected Results

We expect the following results:

a. Ice areal coverage mapping with long-term data from multipolar ENVISAT, polarimetric RADARSAT-2, multipolar ALOS, and other future polarimetric and intereferometric SARs
b. Ingestion of ice area, ice type, and ice thickness data in GCMs
c. Trends in climate change and impact on ice cover, and feedback effects of ice cover on regional and global climate variability in the long term

We expect results on ice cover and thickness or ice mass mapping are to be used to develop winter severity index in the long term for climate change monitoring. Ice freezeup date, breakup date, and ice duration data will be useful to address climate change impact on the Great Lakes ice cover. Long term ice area and ice thickness data can be used to study the interactions and feedback effects of the Great Lakes on regional and global climate.

Ecosystem Change And Effects

Ice cover and its movements impact the regional ecosystems. Ice cover determines the transmittance of PAR (photosynthetically active radiation) depending on snow cover, ice type, and ice thickness [*Bolsenga et al*., 1991]. The duration of ice cover determines the amount of available light for overwintering algae, and is important to seasonal variations in algal mass [*Adrian et al*., 1995]. A bloom of a typical winter-spring phytoplankton community was observed during ice cover [*Vanderploeg et al*., 1992]. Winter ecology can be strongly affected by the ice reduction of ice cover, which influences the environmental and habitat stability of the limnetic community [*Crowder and Painter*, 1991; *Vanderploeg et al*., 1992]. The change modifies and degrades the Great Lakes wetland and deep water habitats of many species. Large concentrations of mallards, American black ducks, and mergansers are found on ice-free areas during winter [*Prince et al*., 1992]. Ice freezeup and ice breakup are related to the timing of seasonal drift and habitat change of *Lethocerus americanus* [*Dubois and Rackouski*, 1992]. The number of days that ice cover exceeded 40% is an important input to the whitefish recruitment forecast model for northern Green Bay and North Shore areas of Lake Michigan [*Brown et al*., 1993]. Knowing the ice cover percentage can provide a quantitative forecast of fish recruitment for applications to marine resource management both by government authorities and by the fishing industry.

Expected Results

We expect the following results:

a. Use of ice area, ice type, and ice thickness data to determine energy fluxes into the lake, especially to determine transmittance of PAR
b. Relationship between ice area and thickness with ecosystem parameters.

The above results show that ice data can be used to address not only direct cryospheric science issues, but also of benefit to more science priorities pertaining to “the Earth’s ice cover and its relationship to the Earth system (e.g. how are global ecosystem changing?)" [Section 2.2 of *NRA-01-OES-03 on Ocean, Ice, and Climate*, 2001].

Hazard Prediction And Mitigation

Ice cover is also important to hazard prediction. Thick ice is a major navigation hazard in the Great Lakes. Ice jams not only impede navigation but can also cause dangerous flooding. Ice imported from southern Lake Huron can create large ice jams on the St. Clair River. Ice passage can be forecast based on the mean surface ice cover fraction, correlated to the presence or absence of the ice arch corresponding to 9.5% and 27.3% ice concentration, respectively [*Daly*, 1992]. To the hydropower industry, ice is potentially harmful to the installations on the Niagara River and elsewhere. Ice rafting causes coastal sediment loss by drifting ice, which is important to coastal erosion processes [*Reimnitz et al.*, 1991] and ice scour can also cause damage to buried lake bottom pipe and power lines. Another ice-related problem is damage to shore structures. Ice cover also affects the transport and distribution of toxins that may have adverse effects on the environment.

Technology Benefit

An objective of GLAWEX 2002 is to map ice thickness with interferometric SAR techniques. There are similarities and differences between lake ice and sea ice. One example of the similarities is that both lake ice and sea ice floats on the water surface. The water surface can be used as natural tie points or reference points to be used in an interferometric inversion algorithm to retrieve thickness. Furthermore, field equipment developed for GLAWEX such as a video system for ice thickness measurements and a telecommunication system and software for satellite imagery and navigation can be used in future field experiments for sea ice.

However, there are major differences between lake ice and sea ice due to differences in fundamental physical characteristics. Lake ice does not contain salinity and thus allows electromagnetic waves to propagate to the bottom, and interferometric data can be used directly for ice thickness inversion (to be verified by GLAWEX 2002). Sea ice contains different amounts of salinity and thus has more loss and limits electromagnetic wave propagation into the ice. For multi-year ice, the salinity can be very low (0 to 1 ppt) which may allow electromagnetic waves to propagate through at appropriate frequencies. In this case, the interferometric SAR technique would be the same as that used for lake ice. For first year ice and younger sea ice, the salinity is typically high and thus limits wave propagation. Nevertheless, salinity in sea ice is a function of ice thickness [*Cox and Weeks*, 1974] which may give rise to different interferometric signatures (phase and correlation magnitude) for different ice thicknesses. Thus, even for first-year sea ice, the capability of interferometric SAR to indirectly measure thickness needs to be investigated in an experimental setup similar to that of GLAWEX 2002 (use AIRSAR and icebreaker ship).

Community Support

The Great Lakes Research Consortium convened a meeting in Alexandria, Virginia in October 1997. Participants from Universities (SUNY, Clarkson), Lake Carriers' Association, US Naval and National Ice Center, US Coast Guard, National Weather Service, US Environmental Protection Agency Great Lakes National Program Office, US Army Corps of Engineers, Canadian Ice Service, Canadian Coast Guard, NOAA Great Lakes Environmental Research Laboratory, and NASA Jet Propulsion Laboratory examined the remote sensing and modeling capabilities of Great Lakes ice conditions, identified important ice coverage parameters, and concluded that ice mapping with advanced radars would meet research and operational needs [*Shen et al*., 1998]. Both the Great Lakes scientific research and operational communities enthusiastically support ice cover mapping including area and thickness with SARs. Continuous use of SARs was strongly recommended by the US Coast Guard and the National Weather Service as one of the conclusions of the 1992-1994 CoastWatch SAR applications demonstration [*Leshkevich et al.,* 1995].

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References

Adrian, R., R. Deneke, U. Mischke, R. Stellmacher, P. Lederer. Long-term study of the Heiligensee (1975-1992) - Evidence for effects of climatic-change on the dynamics of eutrophied lake ecosystems, *Archiv. Hydrobiol*., 133(3), 315-337, 1995.

Assel, R. A., Implications of CO2 global warming on Great-Lakes ice cover, *Clim. Change*, *18*(4), 377-395, 1991.

Assel, R. A. and D. M. Robertson. Changes in winter air temperatures near Lake-Michigan, 1851-1993, as determined from regional lake-ice records, *Limno. and Ocean*., *40*(1), 165-176, 1995.

Bolsenga, S. J., C. E. Herdendorf, D. C. Norton. Spectral transmittance of lake ice from 400-850 nm, *Hydrobiol*., 218(1), 15-25, 1991.

Brown, R. W., W. W. Taylor, and R. A. Assel. Factors affecting the recruitment of lake whitefish in two areas of northern Lake-Michigan, *J. Great Lakes Res*., *19*(2), 418-428, 1993.

Bryan, M.L., A comparison of ERTS-1 and SLAR data for the study of surface water resources, Final Report, ERIM No. 193300-59-F, prepared for the National Aeronautics and Space Administration by the Environmental Research Institute of Michigan, Ann Arbor, MI under Contract No. NAS5-21783, 104 pp.,1975.

Calkins, D. J., D. S. Sodhi, and D. S. Deck. Port Huron Ice Control Model Studies. Proc. of IAHR Int. Symp. on Ice, 1, 361-373, Quebec, Canada, 1981; inclu. Discussion and authors' reply, Quebec, Canada, 1982.

Chase, P.E., Guide to ice interpretation: Satellite imagery and drift ice, Final Report prepared for the U.S. Department of Commerce by The Bendix Corp, Aerospace Systems Division, Ann Arbor, MI, under Contract No. 2-35372, 24 pp.,1972.

Cox, G. F. N., and W. F. Weeks. Salinity variations in sea ice, *J. Glaciol*., *13*(67), 109-120, 1974.

Crowder, A., and D. S. Painter. Submerged macrophytes in Lake Ontario - Current knowledge, importance, threats to stability, and needed studies, *Can. J. Fisheries and Aqua. Sci*., *48*(8), 1539-1545, 1991.

Daly, S. F., Observed ice passage from Lake Huron into the St-Clair river, *J. Great Lakes Res*., *18*(1), 61-69, 1992.

Derecki, J. A., and F. H. Quinn. Record St. Clair River ice jam of 1984, *J. Hydrolic Eng*., *112*(12), 1182-1194, 1986.

Dubois, R.B. and M.L. Rackouski. Seasonal Drift Of *Lethocerus-Americanus* (*Hemiptera*, *Belostomatidae*) In A Lake-Superior Tributary. *Great Lakes Entomologist,* 25 (2): 85-89, 1992.

Goetz, P. W., Ed. in Chief. *The New Encyclopaedia Britannica*, Vol. 5, 15th ed., Chicago, 1990.

Hanson, H. P., C. S. Hanson, B. H. Yoo. Recent Great-Lakes ice trends*, Bull. Amer. Meteo. Soc*., 73(5), 577-584, 1992.

Leshkevich, G.A., Great Lakes ice cover, winter 1974-75, NOAA Technical Report ERL 370-GLERL 11, National Technical Information Service, Springfield, VA 22161, 42 pp., 1976.

Leshkevich, G.A., Machine classification of freshwater ice types from Landsat-1 digital data using ice albedos as training sets, *Remote Sens. Environ.,* 17(3), 251-26, 1985.

Leshkevich, G.A., Deering, D.W., Eck, T.F., and Ahmad, S.P., Diurnal patterns of the bi-directional reflectance of fresh-water ice, *Annals of Glaciology* 14:153-157, 1990.

Leshkevich, G. A., W. Pichel, P. Clemente-Colon, R. Carey, and G. Hufford. Analysis of coastal ice using ERS-1 SAR data, *Int. J. Remote Sens*., 16(17), 3459-3479, 1995.

Leshkevich, G.A., S.V. Nghiem, and R. Kwok. Satellite SAR Remote Sensing of Great Lakes Ice Cover Using RADARSAT Data. In Proceedings: Fourth International Conference on Remote Sensing for Marine and Coastal Environments, Orlando, FL, 17-19 March, ERIM, pp. I-126-134, 1997.

Leshkevich G.A., S.V. Nghiem, and R. Kwok. Monitoring Great Lakes Ice Cover with Satellite Synthetic Aperture Radar (SAR). In Proceedings: International Geoscience and Remote Sensing Symposium (IGARSS2000). IEEE Geosecience and Remote Sensing Society. Honolulu, Hawaii, July 24-28, 2000.

Lofgren, B. M., Simulated effects of idealized Laurentian Great Lakes on regional and large-scale climate, *J. Clim*., *10*(11), 2847-2858, 1997.

Marshall, E.W., Air photo interpretation of Great Lakes ice features, Great Lakes Research Division, Special Report No. 25, University of Michigan, Ann Arbor, MI, p. 89, 1966.

McMillan, M.C., and Forsyth, D.G., Satellite images of Lake Erie ice, January-March 1975, NOAA Technical Memorandum NESS-80, National Technical Information Service, Springfield, VA 22161, 15 pp, 1976.

McGinnis, D.F., and Schneider, S.R., Monitoring river ice breakup from space, *Photogramm. Eng. Remote Sens.* 44(1):57-68, 1978.

Nghiem, S.V., G.A. Leshkevich, and R. Kwok. C-Band Polarimetric Backscatter Observations of Great Lakes Ice. Proceedings, IEEE International Geoscience and Remote Sensing Symposium (IGARSS '98), Seattle, WA, July 6-10, 1998.

Prince, H. H., P. I. Padding, and R. W. Knapton. Waterfowl use of the Laurentian Great-Lakes, *J. Great Lakes Res*., *18*(4), 673-699, 1992.

Reimnitz et al., J. Coastal Res., 7(3), 653-664, 1991.

Rodionov, S. and R. Assel. Atmospheric teleconnection and severity of winters in the Laurentian Great Lakes basin, *Atmos. Ocean*, *38*(4), 601-635, 2001.

Rondy, D.R., Great Lakes ice atlas, NOAA Technical Memorandum NOS LSCR 1, National Technical Information Service, Springfield, VA, 22161, 48 pp, 1971.

Rumer, R.R., Crissman, R., and Wake, A., Ice transport in Great Lakes, Water Resources and Environmental Engineering Research Report No. 79-3 prepared for the Great Lakes Environmental Research Laboratory by the State University of New York at Buffalo, Department of Civil Engineering, and the Center for Cold Regions Engineering, Science and Technology, under Contract No. 03-78-B01-104, 275 pp, 1979.

Schertler, R.J., Mueller, R.A., Jirberg, R.J., Cooper, D.W., Heighway, J.E., Homes, A.D., Gedney, R.T., and Mark, H., Great Lakes all-weather ice information system, NASA Technical Memorandum NASA TM X-71815, National Technical Information Service, Springfield, VA, 22161, 13 pp. and 16 pp. of figures, 1975.

Schmidlin, T. W., Impacts of severe winter weather during December 1989 in the Lake Erie snowbelt, *J. Climate*, *6*(4), 759-767, 1993.

Schneider, S.R., McGinnis, D.F., Jr., and Gatlin, J.A., Use of NOAA/AVHRR visible and near-infrared data for land remote sensing, NOAA Technical Report NESS-84, National Technical Information Service, Springfield, VA 22161, 48 pp, 1981.

Shen, H., S. V. Nghiem, G. A. Leshkevich, and M. Manore. *A summary of current remote sensing and modeling capabilities of the Great Lakes ice conditions*, Occasional Paper Series, Great Lakes Research Consortium, Great Lakes Program, State University of New York at Buffalo, 10 p., 1998.

Smith, J. B., The potential impacts of climate change on the Great-Lakes, *Bull. Amer. Meteo. Soc*., *72*(1), 21-28, 1991.

Sousounis, P. J., and J. M. Fritsch. Lake-aggregate mesoscale disturbances .2. a case-study of the effects on regional and synoptic-scale weather systems, *Bull. Amer. Meteorol. Soc*., *75*(10), 1793-1811, 1994.

Strong, A.E., New sensor on NOAA-2 satellite monitors during the 1972-73 Great Lakes ice season, Remote Sensing and Water Resources Management, Proceedings No. 17, American Water Resources Association, Urbana, IL, pp. 171-178, 1973.

Vanderploeg, H. A., S. J. Bolsenga, G. L. Fahnenstiel, J. R. Liebig, and W. S. Gardner. Plankton ecology in an ice-covered bay of Lake Michigan: utilization of a winter phytoplanton bloom by reproducing copepods, *Hydrobiol*., 243-244, 175-183, 1992.

Wartha, J.H., Lake Erie ice--winter 1975-76, NOAA Technical Memorandum NESS-90, National Technical Information Service, Springfield, VA, 22161, 68 pp, 1977.