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From: Director, Office of Naval Research, Seattle Regional Office, 1107 NE 45th St., Suite 350, Seattle, WA 98105

To: Defense Technical Center, Attn: P. Mawby, 8725 John J. Kingman Rd., Suite 0944, Ft. Belvoir, VA 22060-6218

Subj: RETURNED GRANTEE/CONTRACTOR TECHNICAL REPORTS

1. This confirms our conversations of 27 Feb 97 and 11 Jul 97. Enclosed are a number of technical reports which were returned to our agency for lack of clear distribution availability statement. This confirms that all reports are unclassified and are "APPROVED FOR PUBLIC RELEASE" with no restrictions.

2. Please contact me if you require additional information. My e-mail is *silverr@onr.navy.mil* and my phone is (206) 625-3196.

ROBERT J. SILVERMAN

Applied Physics Laboratory
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AIR • SEA • ICE
Polar Science Center

May 10, 1996

Dr. Michael Van Woert
Office of Naval Research
High Latitude Processes, Code 322HL
800 N. Quincy Street
Arlington, VA 22217-5660

Subj: Final Report, ONR Grant N00014-90-J-1074

Dear Dr. Van Woert:

Enclosed are three copies of our final report for ONR Research Grant N00014-90-J-1074, Surface Heat Flux from AVHRR Ice Surface Temperature. Our principal accomplishments have been published in a series of papers and technical reports. A complete list of the papers and reports is included in our final report as well as abstracts for six papers.

Sincerely yours,

R.W. Lindsay

Ronald W. Lindsay
Co-Principal Investigator

Enclosure: Final Report

cc: Ms. June Hawley, ACO, ONR Seattle
Director, Naval Research Lab
Defense Technical Information Center

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Remote Sensing of Lead Systems and Lead Fluxes
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13. ABSTRACT *(Maximum 200 words)*

Leads are a key component of pack ice. The long-term objective of this series of studies of sea ice has been to observe and understand the role of leads (cracks or open areas in the frozen sea surface) in the surface heat balance of the central Arctic. Specific objectives have been to (1) Learn how to use satellite imagery to identify leads and determine their fractional area coverage, width, orientation, surface temperature and albedo. (2) Determine the heat flux from leads. (3) Determine the surface temperature variability.

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Leads Remote Sensing, 1989-1995

Final Report

1 May, 1996

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PROJECT TITLES:

1989-1991:	Remote Sensing of Lead Systems and Lead Fluxes
1991-1993:	Remote Sensing of Lead Systems and Lead Fluxes
1993-1995:	Surface Heat Flux from AVHRR Ice Surface Temperature

OBJECTIVES

Leads are a key component of pack ice. The long-term objective in this series of studies of sea ice has been to observe and understand the role of leads in the surface heat balance of the central Arctic. The specific objectives have been to:

1. Learn how to use satellite imagery to identify leads and determine their fractional area coverage, width, orientation, surface temperature and albedo. Our principal data sources have been AVHRR and Landsat images. Much of this effort required us to learn how to quantitatively determine the surface temperature and albedo using AVHRR images, including all of the required calibrations and corrections.

2. Determine the heat flux from leads. The sensible heat flux from winter leads is often opposite in sign and one or two orders of magnitude larger than what is commonly found over thick pack ice. The flux from leads often reverses the regional average heat flux and as a consequence changes the mean structure of the lower atmospheric boundary layer from stable to unstable.

3. Determine the surface temperature variability. Much of the surface temperature variability is in leads, and we have sought to determine the spatial scales of this variability in different ice conditions, to determine the proportion of the variability lost by the 1-km resolution in AVHRR images, and to account for AVHRR's coarse resolution in making estimates of the surface sensible heat flux.

ACCOMPLISHMENTS

Our principal accomplishments have been published in a series of four papers, with additional results published in another four papers (see below for a complete list). We have two more papers that are nearing completion.

1. Lindsay, R. W. and D. A. Rothrock, 1994: Arctic sea ice surface temperature from AVHRR, *J. Climate.* **7**, 174-183.

   Abstract:
   The surface temperature of Arctic sea ice is estimated using the infrared channels of the Advanced Very High Resolution Radiometer (AVHRR) on satellites NOAA-10 and NOAA-11. Temperature statistics are analyzed for 478 cells measuring 200 km square distributed over the entire Arctic Basin throughout 1989. The images are cloud masked manually, and the surface temperature of the cloud-free area is estimated using an algorithm specific to Arctic pack ice. The rms error of the estimate is thought to be about 3.2°C, largely due to uncertainty in cloud masking and the lack of knowledge of haze and ice crystal precipitation occurrence. The mean temperatures of the cells range from near 0°C in summer to below –45°C in winter. Monthly averages range down to –40°C for the central Arctic and –29°C for the peripheral seas. The monthly-average standard deviation within cells in the central Arctic is highest in November (2.2°C) and drops to almost 0°C in the summer. It is commonly twice as large in the peripheral seas as in the central Arctic. We also formulate a computation of the sensible heat flux at the surface based on the spatial variations of the surface temperature estimated with AVHRR. The contribution to the heat flux by the thin ice and leads that contribute to the spatial variability is found to be 8 W m^{-2} larger in the central Arctic than found in earlier estimates.

2. Lindsay, R. W. and D. A. Rothrock, 1994: Arctic sea ice albedo from AVHRR, *J. Climate*, **7**, 1737-1749.

   Abstract:
   The seasonal cycle of surface albedo of sea ice in the Arctic is estimated from measurements made with the Advanced Very High Resolution Radiometer (AVHRR) on the polar orbiting satellites NOAA-10 and NOAA-11. The albedos of 145 200-km-square cells are analyzed. The cells are from March through September 1989 and only include those for which the sun is more than 10° above the horizon. Cloud masking is performed manually. Corrections are applied for instrument calibration, nonisotropic reflection, atmospheric interference, narrowband to broadband conversion, and normalization to a common solar zenith angle. The estimated albedos are relative, with the instrument gain is set to give an albedo of 0.80 for ice floes in March and April. The mean values for the cloud-free portions of individual cells range from 0.18 to 0.91. Monthly averages of cells in the central Arctic range from 0.76 in April to 0.47 in August. The monthly averages of the within-cell standard deviations in the central Arctic are 0.04 in April and 0.06 in September. The surface albedo and surface temperature are correlated most strongly in March ($R = -0.77$) with little correlation in the summer. The monthly average lead fraction is determined from the mean potential open water, a scaled representation of the temperature or albedo between 0.0 (for ice) and 1.0 (for water); in the central Arctic it rises from an average 0.025 in the spring to 0.06 in September. Sparse data on aerosols, ozone, and water vapor

in the atmospheric column contribute uncertainties to instantaneous, area-average albedos of 0.13, 0.04, and 0.08. Uncertainties in monthly average albedos are not this large. Contemporaneous estimation of these variables could reduce the uncertainty in the estimated albedo condsiderably. The poor calibration of AVHRR channels 1 and 2 is another large impediment to making accurate albedo estimates.

3. Lindsay, R. W. and D. A. Rothrock, 1995: Arctic sea ice leads from Advanced Very High Resolution Radiometer images, *J. Geophys. Res.*, **100** (C3), 4533-4544.

Abstract:
A large number of advanced very high resolution radiometer (AVHRR) images from throughout 1989 are analyzed to determine lead characteristics. The units of analysis are square 200-km cells, and there are 270 such cells in the data set. Clouds are masked manually. Leads are determined from images of the potential open water δ, a scaled version of the surface temperature or albedo that weights thin ice by its thermal or brightness impact. The lead fraction is determined as the mean δ; the monthly mean lead fraction ranges from 0.02 in winter to 0.06 in summer in the central Arctic and is near 0.08 in the winter in the peripheral seas. A method of accounting for lead width sampling errors due to the finite sample areas is introduced. In the central Arctic the observed mean lead width for a threshold of $\delta = 0.1$ ranges from 2 or 3 km (near the resolution of the instrument) in the winter to 6 km in the summer. In the peripheral seas it is about 5 km in the winter. Width distributions are often more heavily weighted in the tail than exponential distributions and are well approximated by a power law. The along-track, number density power law $N = aw^{-b}$ has a mean exponent of $b = 1.60$ (standard deviation 0.18) and shows some seasonal variability. Mean floe widths in the central Arctic are 40 to 50 km in the winter, dropping to about 10 km in the summer. For floes the power law has a mean exponent of 0.93 and exhibits a clearer annual cycle. Lead orientation is determined with a method based on the direction of maximum extent.

4. Lindsay, R. W., D. B. Percival, and D. A. Rothrock, 1996: The Discrete Wavelet Transform and the Scale Analysis of the Surface Properties of Sea Ice, *IEEE Trans. Geoscience and Remote Sensing*, in press.

Abstract:
The formalism of the one-dimensional discrete wavelet transform (DWT) based on Daubechies wavelet filters is outlined in terms of finite vectors and matrices. Both the scale-dependent wavelet variance and wavelet covariance are considered and confidence intervals for each are determined. The variance estimates are more accurately determined with a maximal-overlap version of the wavelet transform. The properties of several Daubechies wavelet filters and the associated basis vectors are discussed. Both the Mallat orthogonal-pyramid algorithm for determining the DWT and a pyramid algorithm for determining the maximal-overlap version of the transform are presented in terms of finite vectors. As an example, we investigate the scales of variability of the surface temperature and albedo of spring pack ice in the Beaufort Sea. The data analyzed are from individual lines of a Landsat TM image (25-m sample interval) and include both reflective (channel 3, 30-m resolution) and thermal (channel 6, 120-m resolution) data. The wavelet variance and covariance estimates are presented and more than half of the variance is accounted for by scales of less than 800 m. A wavelet-based technique for enhancing the lower-resolution thermal data using the reflected data is introduced. The simulated effects of poor instrument resolution on the estimated lead number density and the mean lead width are investigated using a wavelet-based smooth of the observations.

The two papers that are nearing completion are:

5. Rothrock, D. A. and R. W. Lindsay: Regional average heat flux from leads

Abstract
The regionally averaged turbulent and radiative heat fluxes from leads are determined using high-resolution satellite and aircraft observations of the surface temperature. We determine the heat flux from leads by extracting sets of one dimensional transects from two dimensional thermal images of sea ice or by using surface temperature measurements from aircraft transects. The flux from the leads is found by comparing the lead surface temperature to the temperature of the nearby floes. A fixed wind speed is assumed. We outline the details of the procedures used for determining the sensible, latent, and radiative heat fluxes from leads and the properties of the heat transfer coefficients used in these calculations, we then use this procedure on eighteen Landsat scenes and two aircraft transects and then determine the spatial scales important for lead heat fluxes. The spatial scales that are important for the flux from leads are determined using low-pass filtered versions of the data with filters based on the orthogonal discrete wavelet transform. A correction procedure for low-resolution data is determined. Finally, we estimate the heat flux from leads for 114 AVHRR scenes from throughout the cold seasons of a single year.

6. Lindsay, R. W.: Spatial variability of the surface temperature of sea ice.

Abstract
The spatial scales of the variability of the surface temperature of sea ice are determined with the use of the discrete orthogonal wavelet transform. The wavelet variance is determined for 18 Landsat TM images from both the Arctic and the Antarctic for scales ranging from 30 m to 30 km. Aircraft and AVHRR data are also analyzed, extending the range of scales observed to 1 m to 100 km. The degree of spatial concentration of the variance is determined and the relationships between the sensible heat flux and the spatial variability are determined. The lead width distribution and the lead width/lead temperature bivariate distributions are determined and compared to various parameterized distributions.

SUMMARY OF PAPERS PUBLISHED

Papers published (refereed journals)	8
Technical reports (non-refereed)	5
Papers in progress	2

Papers Published:

Lindsay, R. W., D. B. Percival, and D. A. Rothrock, 1995: The Discrete Wavelet Transform and the Scale Analysis of the Surface Properties of Sea Ice, *IEEE Trans. Geoscience and Remote Sensing*, in press.

Lindsay, R. W. and D. A. Rothrock, 1995: Arctic sea ice leads from Advanced Very High Resolution Radiometer images, *J. Geophys. Res.*, **100** (C3), 4533-4544.

Percival, D. B., 1995: On estimation of wavelet variance. *Biometrika*, **82**, 619-631.

Yu, Y., D.A. Rothrock, and R.W. Lindsay, 1995: A comparison between AVHRR-derived surface temperatures in the Arctic and surface in-situ measurements, *J. Geophys. Res.*, **100** (C3), 4525-4532.

Lindsay, R. W. and D. A. Rothrock, 1994: Arctic sea ice surface temperature from AVHRR, *J. Climate*. **7**, 174-183.

Lindsay, R. W. and D. A. Rothrock, 1994: Arctic sea ice albedo from AVHRR, *J. Climate*, **7**, 1737-1749.

Lindsay, R. W. and D. A. Rothrock, 1993: The calculation of surface temperature and albedo of Arctic sea ice from AVHRR, *Ann. Glaciol.*, **17**, 391-397.

Steffen, K., B. Bindschadler, C. Casassa, J. Comiso, D. Eppler, F.Fetterer, J. Hawkins, J. Key, D. Rothrock, R. Thomas, R. Weaver, and R. Welch, 1993: The outlook for AVHRR applications to polar surface observations, *Ann. Glaciol.*, **17**, 1-16.

Technical reports (non-refereed):

Lindsay, R.W., A.T. Jessup, J.A. Francis, 1995: Surface temperature and lead heat fluxes from aircraft surveys during LEADEX, Proc. Amer. Meteor. Soc. *4th Conf. on Polar Meteorology and Oceanography*, January 1995, Dallas, TX.

Lindsay, R.W., 1994: Heat flux from leads in pack ice from a Landsat TM image. *OCEANS 94*, Brest, France, September 1994, Proc. IEEE Conf., 3, 606-611.

Lindsay, R. and D. Rothrock, 1992: The spatial structure of the surface temperature field of Arctic pack ice determined with AVHRR, *3rd Conf. on Polar Meteorology and Oceanography*, 29 Sept - 2 Oct., 1992, Portland, Oregon, Amer. Met. Soc., 76-79.

Rothrock, D.A., 1992: Ice thickness observations from satellites, *Report of the Sea Ice Thickness Workshop*, 19-21 November 1991, New Carrollton, Maryland, Applied Physics Laboratory, 1013 NE 40th St., Seattle, WA 98105, pp. B60 - B65.

Thorndike, A.S., C. Parkinson, and D.A. Rothrock, eds., *Report of the Sea Ice Thickness Workshop*, 19-21 November 1991, New Carrollton, Maryland, Applied Physics Laboratory, 1013 NE 40th St., Seattle, WA 98105, 1992.

Papers in progress (not yet submitted):

Rothrock, D. A. and R. W. Lindsay: Regional Average Heat Flux from Leads

Lindsay, R. W.: Spatial variability of the surface temperature of sea ice.