Quantifying Sea Ice in the Southern Ocean Using ArcGIS

Tracy L. DeLiberty, Cathleen A. Geiger and Mary D. Lemcke

Abstract: A National Science Foundation (NSF) project is underway with researchers at the University of Delaware, the Australian Antarctic Division, the National Ice Center (NIC) and Clarkson University to evaluate two datasets - in situ (point) sea-ice thickness observations and weekly ice charts (polygon). The goal is to ascertain their quality for use in monitoring sea-ice thickness and mass balance changes in the Southern Ocean. Sea-ice thickness calculations from both datasets are temporally joined with spatially averaged in situ observations matching their respective NIC ice chart using ArcGIS's field calculator, attribute query, spatial join and dissolve tools. The uncertainties of total ice thickness for both in situ observations and NIC ice charts are propagated through individual calculations and GIS tools. A composite product of the two datasets and their error estimates is being developed for monitoring sea-ice thickness, mass balance and validation fields for climate modeling. ArcGIS is used for the analysis of sea-ice conditions over the 1995-2000 period of study by visually and quantitatively examining the spatial extent of sea-ice and the variability of sea ice thickness for selected weeks during 1995 and 1998. The 3D Analyst extension also provides a means for displaying sea-ice thickness fields by draping the errors over the thickness estimates.

Introduction

Sea-ice covers approximately 7% of the earth's oceans at any time (Parkinson and Washington 1979), greatly affecting the exchange of energy between the ocean and the atmosphere and increasing the albedo of the polar regions. Antarctic sea ice is an important feature of the global climate system because it is a sensitive indicator of climate change and therefore plays a complex role in global climatic and oceanographic processes. For these reasons, sea ice is also referred to as a climatological canary or early warning detector of change. Comprised of mostly thin, first-year ice, Antarctic sea ice extends to a latitude of about 60º S except within the Weddell Sea sector where it may extend further northward (King and Turner 1997). At its maximum extent, Antarctic sea ice covers 20% more area than its Arctic counterpart (Comiso et al. 1992) and has a much larger seasonal variation, about 80%, or $16X10^6$ km^2, than that observed in the Arctic (King and Turner 1997).

Large-scale general circulation modeling studies indicate that Antarctic sea ice will exhibit changes in extent, thickness, and compactness in response to long-term changes in global climate as well as short-term climate variations (Ledley 1991, Rind et al. 1995, Jacobs and Comiso 1997, Geiger et al. 1997). Most models agree that atmospheric warming will result in a reduction in northern hemispheric ice cover. On the contrary, the southern ice cover modeling results produce conflicting responses in global warming scenarios. Moreover, the variability in sea-ice conditions are poorly understood due to the current lack of long-term and large-scale thickness observations within the Southern Ocean. At this time, there is no comprehensive climatology of Antarctic sea-ice conditions to validate such large-scale models or to study past trends (Worby and Ackley 2000, Geiger et al. 2000).

A National Science Foundation project is underway to ascertain the quality of the two largest operational data products that currently exist for monitoring sea-ice thickness and mass balance changes in the Southern Ocean. These are the National Ice Center weekly ice charts and a collection of over 20,000 in situ ship-based ice observations. A recent study comparing thickness estimates obtained using NIC ice charts to ship-based observations within the Ross Sea sector showed a correlation between satellite-derived and in situ estimates (Schellenberg 2002). These preliminary findings suggest potential usefulness of the NIC data to develop a continental-scale sea-ice climatology. This paper reports on our sea-ice comparison from conditions during two contrasting years, 1995 and 1998. Specifically we report on the development of the spatial-temporal database to compare the NIC ice charts with the ship-based observations, and the tools used to analyze the sea-ice extent and thickness. Problems encountered in using ArcGIS in the southern polar region along with our solutions will be discussed in our presentation.

Data

This study focuses on the Ross Sea sector (Figure 1) of the Southern Ocean, which extends from 150 ºE longitude to 150 ºW longitude. It examines two different types of sea-ice thickness data: ship-based observations and weekly ice chart information.

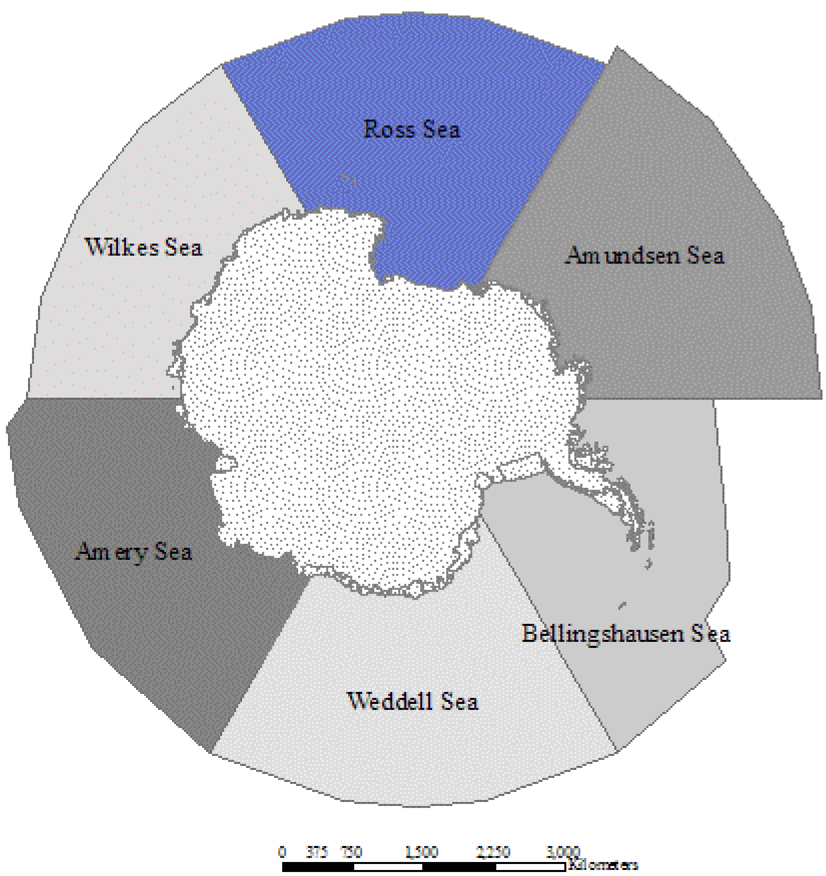

Figure 1. Area of study includes the Ross Sea in the Southern Ocean.

The Scientific Committee on Antarctic Research (SCAR) developed the Antarctic Sea Ice Processes and Climate (ASPeCt) program to compile and standardize an extensive archive of ship observations. The ASPeCt program has identified data collected during 80 voyages resulting in more than 20,000 individual records of Antarctic sea ice conditions since 1980. Sea-ice thickness is reported from ranges of actual thickness from individual point locations or using the proxy of sea-ice type. Individual point observations are made by trained ice observers who estimate ice thickness, in centimeters, as the ice turns sideways along a ship's hull moving past a ball of known diameter hung over the side (Worby 1999). Five cruises are chosen for this initial analysis based on their location and time period as validation data sets to compare with weekly ice charts. These include ship voyages from May/June 1995, August 1995, May/June 1998, December 1998/January 1999, and December 1999/January 2000.

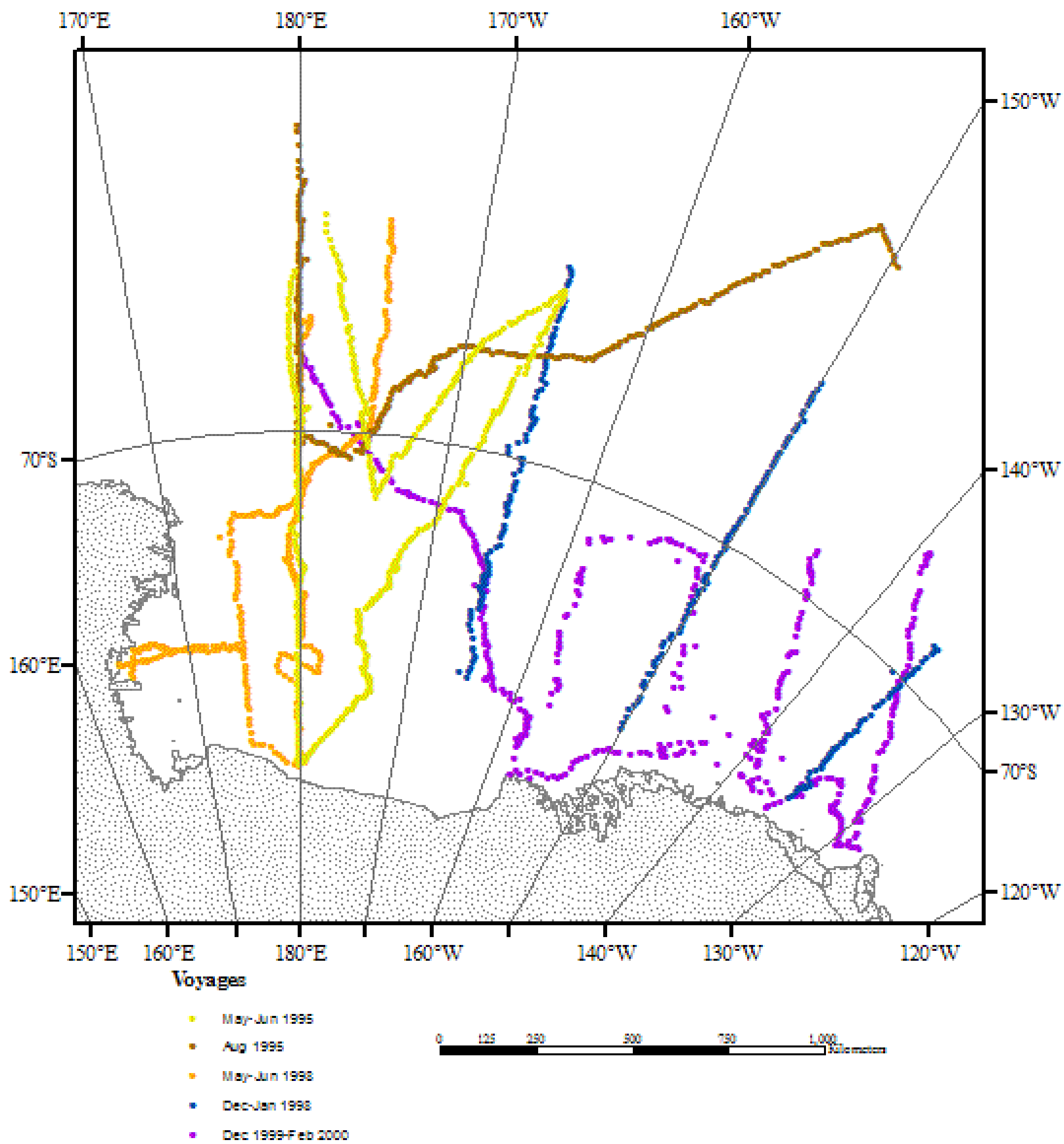

Figure 2. Ship-based observations as part of five separate voyages in the Ross Sea during 1995 through 2000.

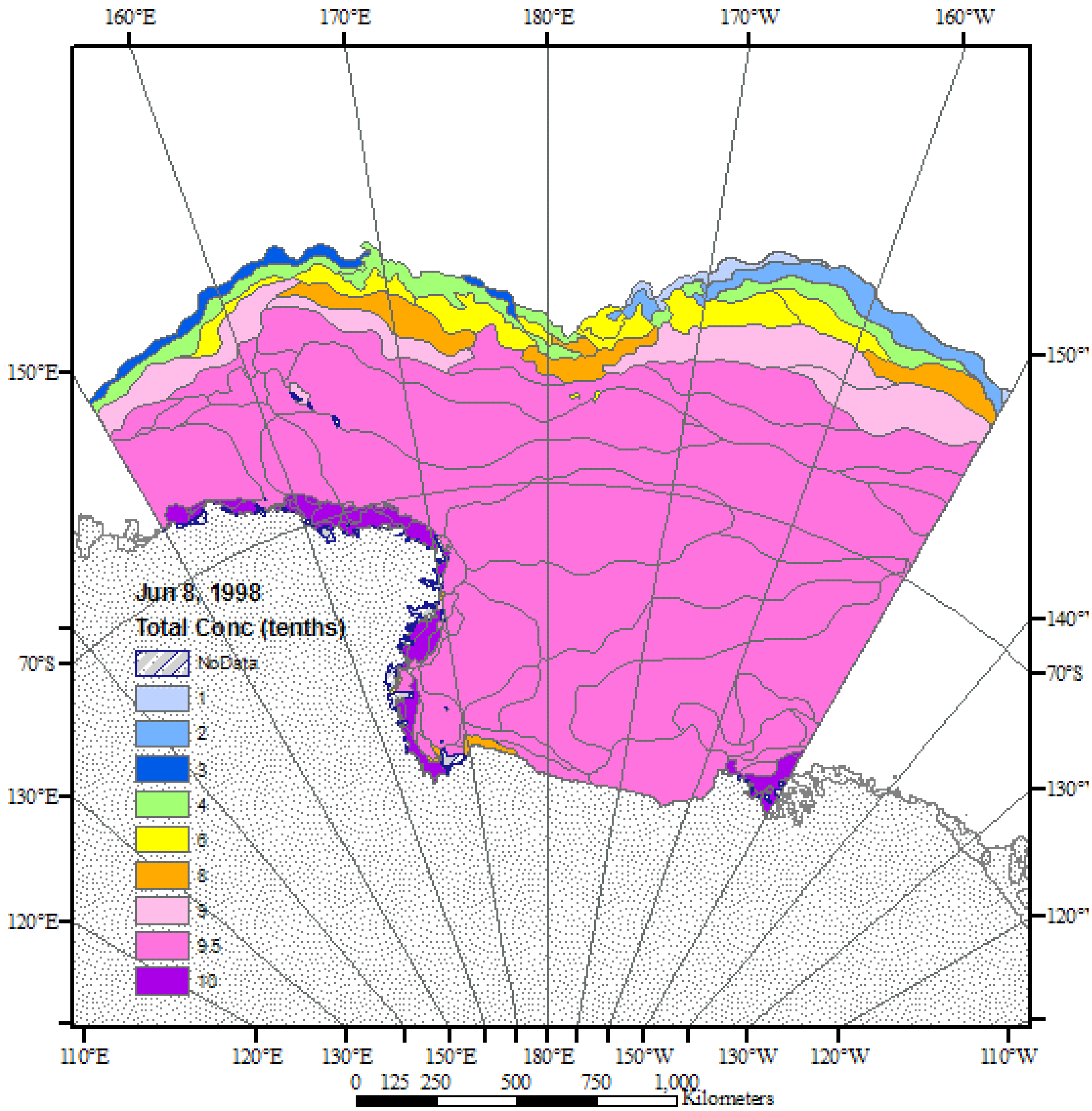

Figure 3. Weekly NIC ice chart spatially subset over the Ross Sea during the week of June 8, 1998. Each polygon contains sea-ice information including total ice concentration and stage of development.

The NIC, a joint organization sponsored by the U.S. Navy, the National Oceanic and Atmospheric Administration (NOAA), and the U.S. Coast Guard, has produced weekly ice charts for the Southern Ocean since the early 1970's. These sea-ice charts are produced by trained sea-ice analysts, who discern sea-ice concentration and stage of development information using aircraft reconnaissance, visible and infrared Advanced Very High Resolution Radiometer (AVHRR) and Operational Line Scanner (OLS) imagery, passive microwave including Electrically Scanning Microwave Radiometer (ESMR), SMMR, and SSM/I data, active microwave Synthetic Aperature Radar (SAR) data, and freezing degree-day models (NIC et al. 1996, Schellenberg et al. 2002). Charts of sea ice in Digital Form (SIGRID) are available from 1973 to 1994 on CD-ROM from 1995 to October 1997 on paper charts, and GIS form starting in October 1997 (Dedrick et al. 2001). The NIC charts are produced weekly, reporting average ice conditions integrated from data usually collected over a 72-hour period. The NIC sea-ice charts incorporate discrete polygons to characterize homogenous sea-ice conditions with information on sea-ice concentration, stage of development, and form as mandated by the World Meteorological Organization (WMO 1970).

Methods of Analysis

This section discusses the calculations of sea-ice thickness from both datasets, their comparison, and the analysis of sea-ice conditions. The in situ ship measurements were imported into ArcGIS 8 as a spatially referenced geodatabase data structure which catalogues properties for each of three partial categories (thickest, middle, thinnest partial) of ice concentration, thickness, type, topography, amounts of ridged ice and ridge sale heights, and snow depths, as well as overall open water and open water fraction. Estimates of sea-ice thickness were calculated, in centimeters, for the level ice (T_{level}), ridged ice (T_{ridge}), and snow thicknesses (T_{snow}) which together are used to estimate the total ice thickness (Schellenberg 2002).

$$T_{\text{total}} = T_{\text{level}} + T_{\text{ridge}} + T_{\text{snow}} \quad [1]$$

Each in situ sea-ice concentration and thickness estimate has an associated uncertainty. Empirically determined uncertainties for sea-ice concentration and thickness estimates are computed from ship-based observations following standard rules of error propogation (Schellenberg 2002: 34). These calculations were implemented utilizing the ArcMap's field calculator.

Thickness estimates, in centimeters, calculated from weekly NIC ice charts use sea-ice concentration (C_i) and stage of development (S_i) observations for the thickest (1), middle (2), and thinnest (3) ice within each sea-ice polygon as is also done for the in situ ship observations. Stage of development is a quantifiable indicator of ice type determined from remotely sensed data. Specific ice types are associated with a thickness range that serves as a proxy for sea-ice thickness and used here to estimate total (T_{NIC}) ice thickness (Schellenberg 2002).

$$T_{\text{NIC}} = \frac{C_1}{10} \times S_1 + \frac{C_2}{10} \times S_2 + \frac{C_3}{10} \times S_3 \quad [2]$$

As with the ship thickness estimates, NIC ice chart concentration and thickness estimates has an associated level of uncertainty (Schellenberg, 2002: 31-34).

The next step is to evaluate the utility of sea-ice thickness estimates derived from satellite products produced by the NIC. The in situ and NIC datasets are spatially defined in their respective native coordinate systems and projection in ArcCatalog and reprojected to a common South Pole Lambert Azimuthal Equal Area spatial reference in ArcToolbox. Next, the two datasets are temporally and spatially merged by temporally querying the hourly ship-based observations coincident with a weekly ice chart using ArcMap's attribute query tool (attribute query search on date field – date ≥ #5/7/1998# and date ≤ #5/12/1998#), and then, spatially joining (Figure 4 and 5) the coincident hourly ship observations with the NIC weekly ice chart using ArcMap's spatial join tool..

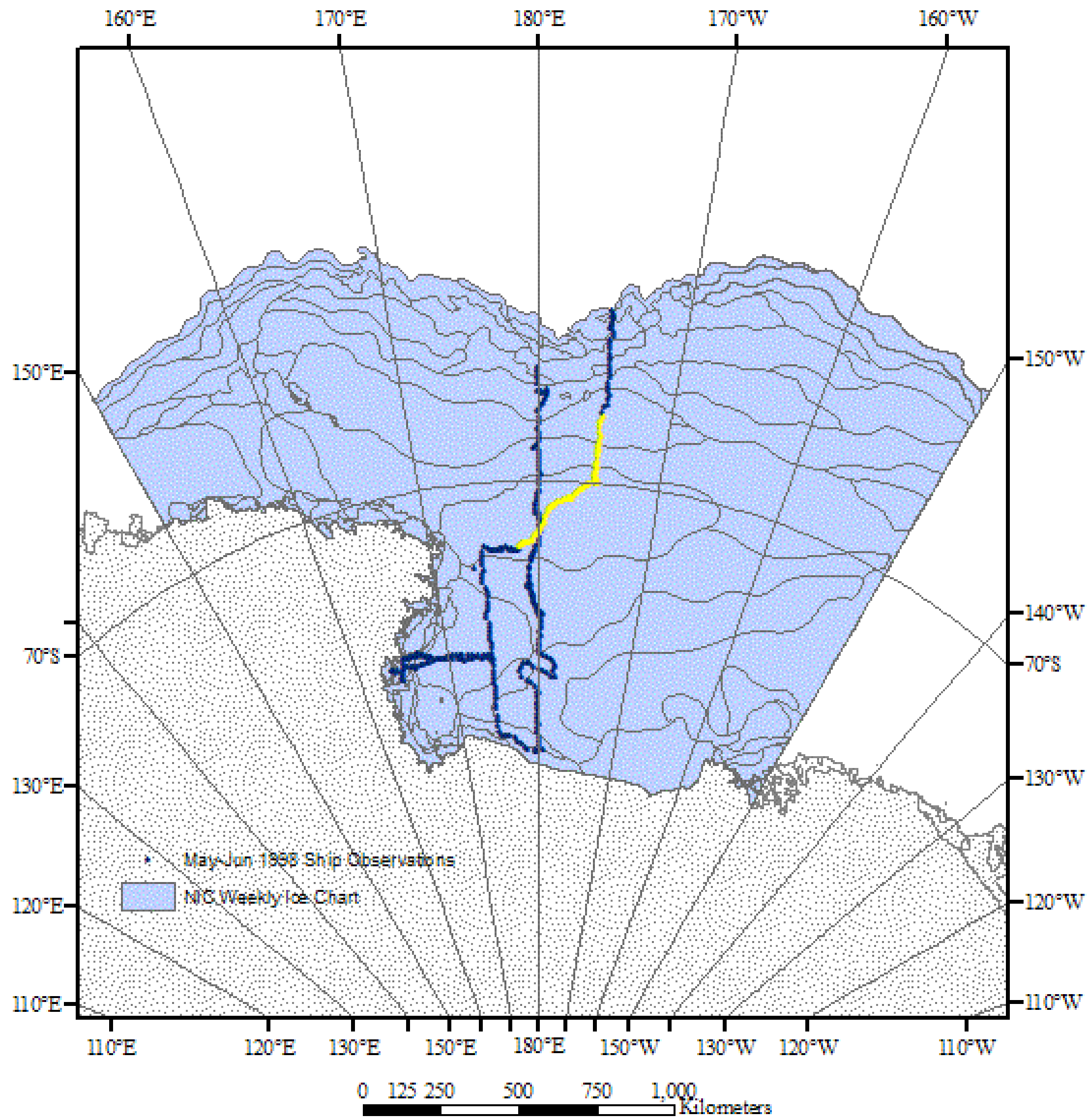

Figure 4. Ship based observations (point data) during a May/June 1998 voyage overlayed on a weekly NIC ice chart (polygons data). Yellow dots represent coincident ship observations with the ice chart during the week of June 8, 1998.

This procedure resulted in a joined table of spatially coincident points overlayed on the weekly NIC polygons. The ship observation points are then averaged within each NIC polygon to obtain an average ship thickness within each respective polygon using the dissolve tool to aggregate the point observations. An accompanying uncertainty is also computed. The NIC thickness and ship thickness estimates are evaluated using graphical as well as statistical measures (mean absolute error-MAE, root mean squared error-RMSE and R^2).

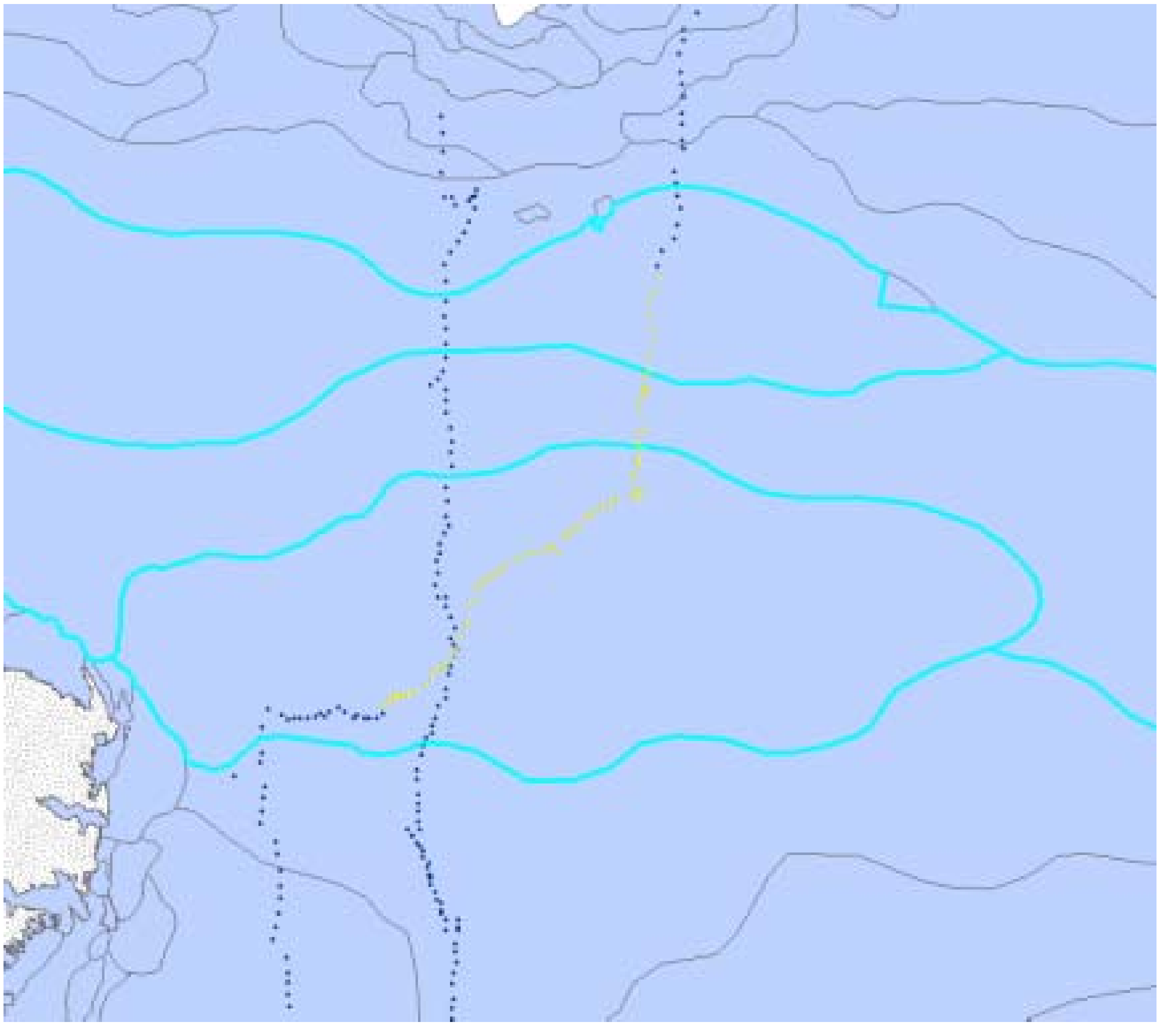

Figure 5. Zoom in view of temporally and spatially coincident ship-based observations (yellow) with a weekly ice chart polygons highlighted in cyan.

Comparison of NIC Ice Charts and Ship-Based Observations

Figure 6 shows the scatter around the one-to-one comparison line with error bars for each coincident multi-point, ship observation and NIC polygon. Overall, the NIC ice charts tend to underestimate ice thickness, particularly thinner ice. A temporal bias is evident in May, and especially June of 1998, with the ice charts underestimating the thickness. The random scatter of this plot results in a relatively low correlation (0.6). A similar comparison was made during the decay season from December through February. We are currently examining outliers on this and other scatterplots to understand mismatches in measurement abilities between these two data sets.

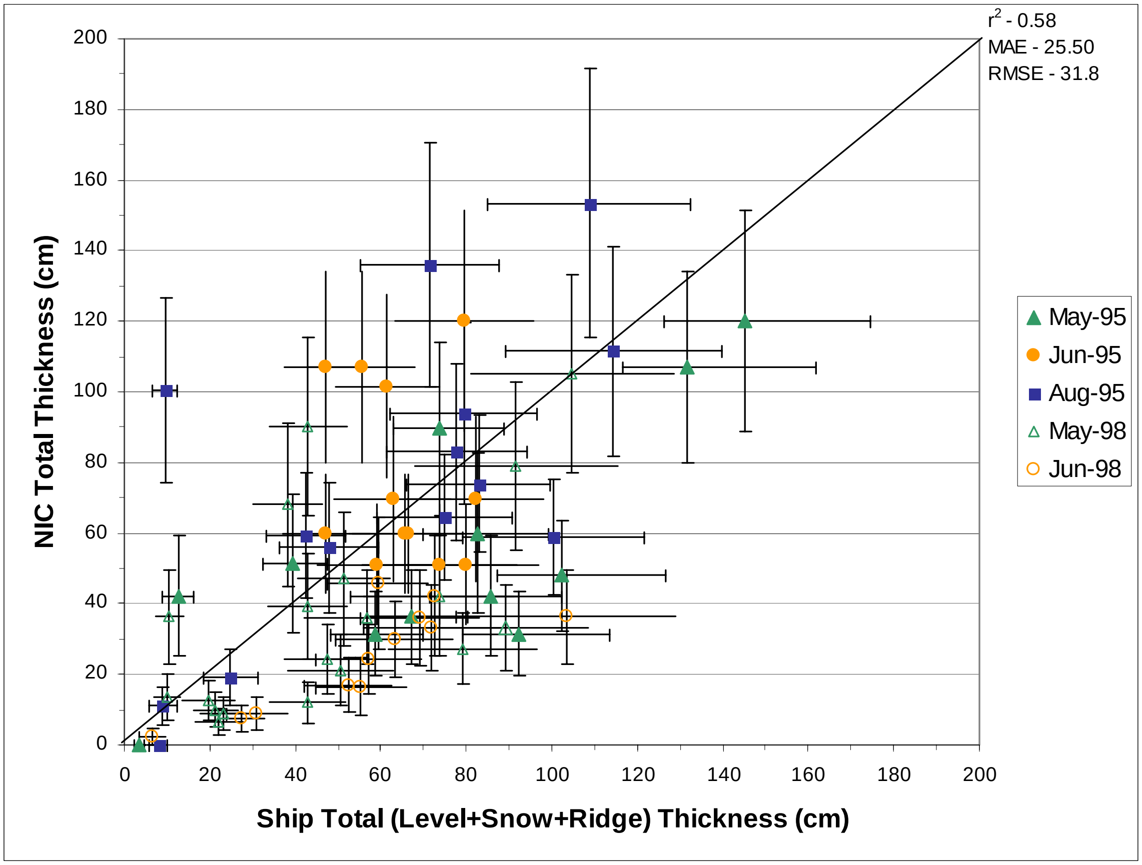

Figure 6. Scatterplot comparing the thickness estimated from the NIC ice chart and ship-based measurements for the growth season of 1995 and 1998.

The year-to-year variability in thickness is evident in Figure 7 with much thinner sea ice in 1998, a strong El Nino year, as compared to 1995. Although these scatterplots show overall agreement between NIC information and in situ ship-based observations, we currently make use of the GIS to further investigate spatial bias that may be attributed to differences from analysts' level of experience, remotely sensed data analyzed, and/or procedural changes at the NIC.

Overall, the NIC ice chart thickness estimates correlate reasonably well with *in* situ observations. Both of these data sets are currently the only continental scale data to examine the seasonal and interannual thickness distribution and mass balance of sea-ice in the Southern Ocean. A blended product is under development to merge estimates of ship-based thickness with areal extent of sea-ice conditions as represented by the NIC polygons.

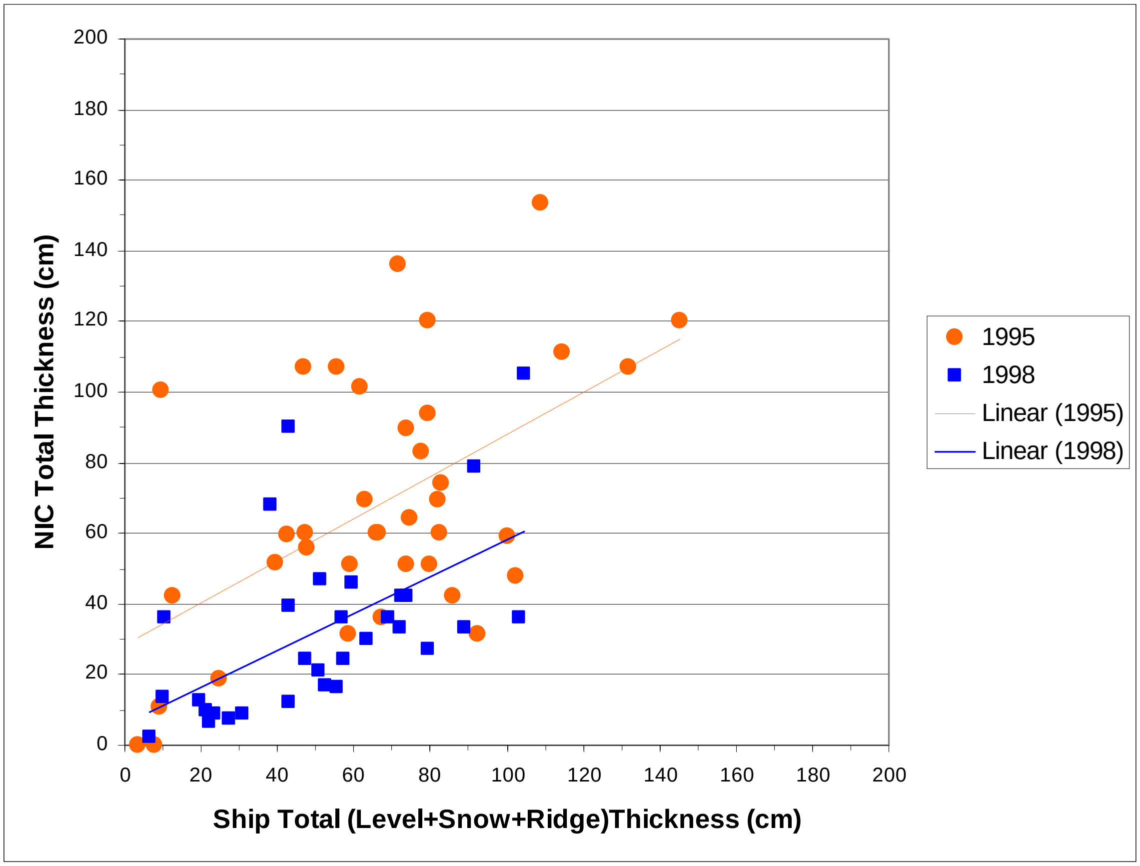

Figure 7. Scatterplot comparing the thickness from the NIC ice charts and ship-based observations as in Figure 7 without the error bars with the linear regression line for 1995 and 1998 superimposed on the points.

Analysis of Sea-Ice Thickness

Using the NIC charts, the sea-ice extent, seasonal and interannual thickness distribution and the mass balance are derived for the Ross Sea. This will be used to establish a framework for creating a Southern Hemisphere sea-ice thickness climatology and enable the detection of any trends in the distribution of Antarctic sea-ice thickness. The analysis performed in ArcGIS provides visual and quantitative tools for examining sea-ice extent and spatial and interannual variability between the growth and melt seasons.

The visual analysis afforded in ArcMap enables the extent of sea-ice (Figure 8) to be tracked and the spatial variability in the pack to be investigated. The sea-ice extends to 61ºS latitude in June 1995 and to 60ºS latitude in June 1998, and continues to increase northward towards the maximum in September (not shown). During the melt season in January 1999 and 2000, the sea ice extends to only 63ºS latitude in the western portion of the Ross Sea sector with a minimum in February. Using the GIS, researchers are able to depict the advancement and retreat of sea ice through the annual cycle, as well as determine the area of sea-ice cover. Additionally, the visual comparison of the spatial fields in the GIS enable the interannual variability in sea-ice conditions to be monitored between years. As shown in Figure 5 (upper panel), sea ice is not as thick during June 1998 as in June 1995 with the larger areal extent of first-year thick (light pink) and multi-year sea ice (darker pink) even though the sea-ice extent is greater in 1998. This relationship does not occur in January. In January 1995, a larger areal extent of first-year thick ice is found, but a greater spatial extent of multi-year ice occurs in 1998. The GIS enables a detailed investigation of the sea-ice thickness during these periods.

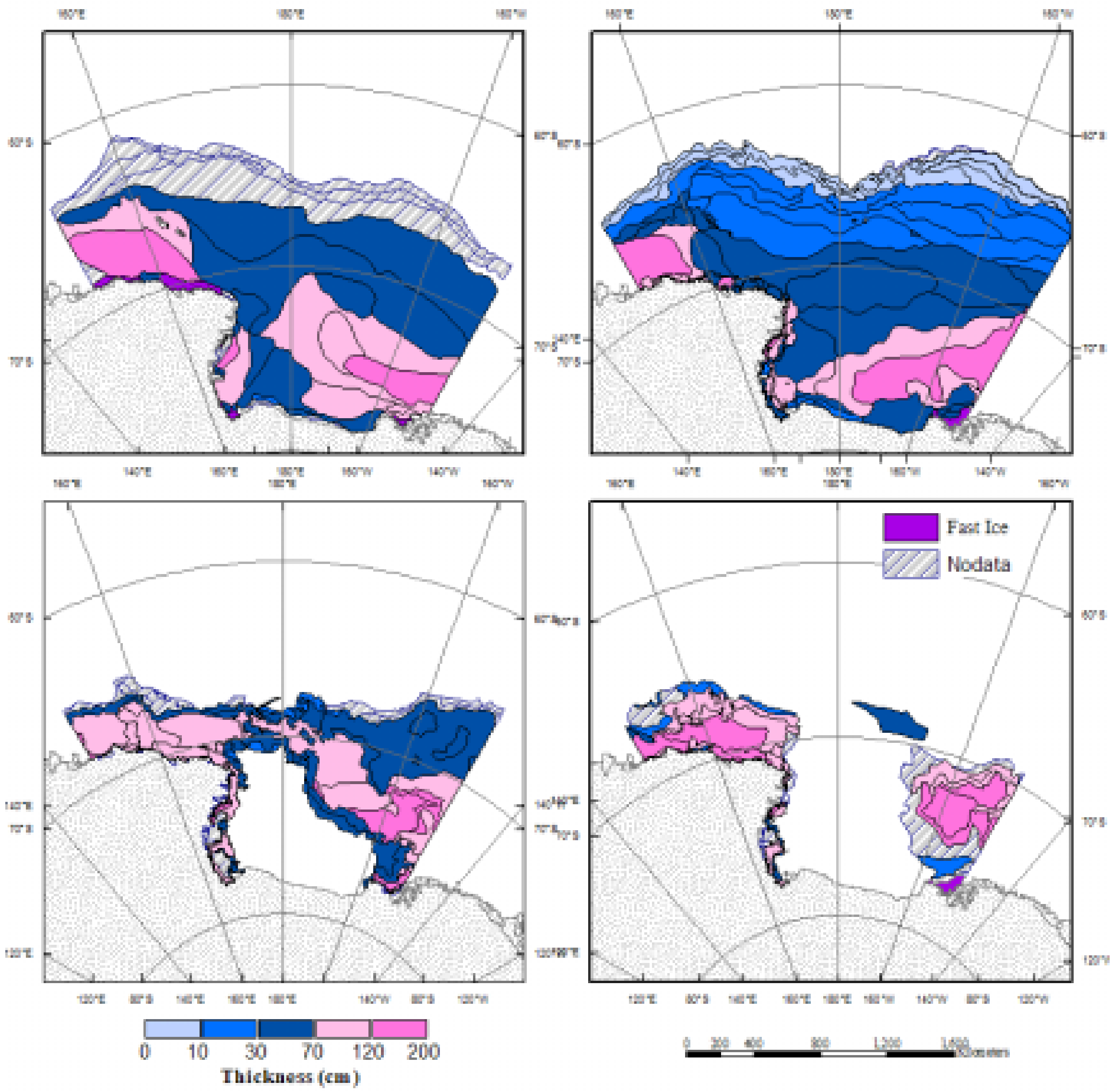

Figure 8. Sea-ice thickness during the week of June 8, 1995 (upper left) and 1998 (upper right) and January 24, 1999 (lower left) and 2000 (lower right).

ArcGIS 3D Analyst extension provides an enhanced view of sea-ice conditions (Figure 9a) not offered in GIS's traditional flat plane view of an area (Figure 8). In addition, the errors associated with a field can be draped over the field of interest. Figure 9b displays the uncertainty in the sea-ice thickness estimates (Figure 9a) draped over the thickness field. The thickness errors are color coded with the smallest errors shown in green graduated to the largest errors in red. The thinnest sea ice (0-10 cm) along the fringe of the ice pack contains errors of ±2.5-5 cm (shown in green) and the thickest ice (120-200 cm) with errors of ±35cm (shown in red). These error estimates are important to determine the quality of sea-ice thickness and mass balance (not shown). This is critical in the context of quantifying the variability and the detection of trends in the data to verify if the results are statistically significant.

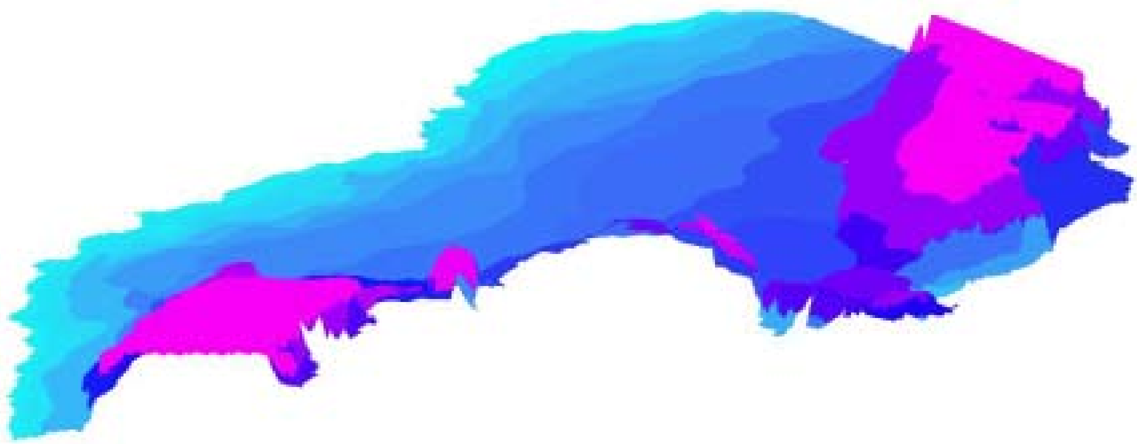

Figure 9a. 3-dimensional display of sea-ice thickness during the week of June 8, 1998 with thin ice displayed in light blue and thick ice shown in purple.

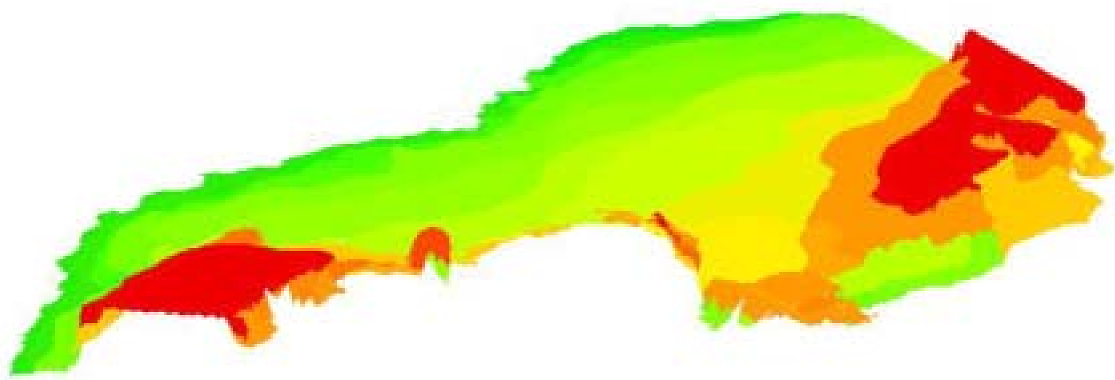

Figure 9b. Sea-ice thickness errors (light green represents small errors gradating to large errors displayed in red) draped over 3D sea-ice thickness field (Figure 9a).

One of the main goals of this research is to compute monthly thickness distribution for the Ross Sea. The term "thickness distribution" refers to how ice is distributed from its thinnest to thickest form with the variability of that distribution of great interest over the seasonal cycle. During the 1998 annual cycle, the growth and melt seasons are resolved in percentages of open water and thin and thicker ice types. In the decay season, the sea-ice pack is largely distributed between open water and the thickest ice that has survived the melt season (1st year medium/thick and multi-year ice), while in July through September the pack is distributed into the thinner ice categories as the growth season is reaching its maximum in September.

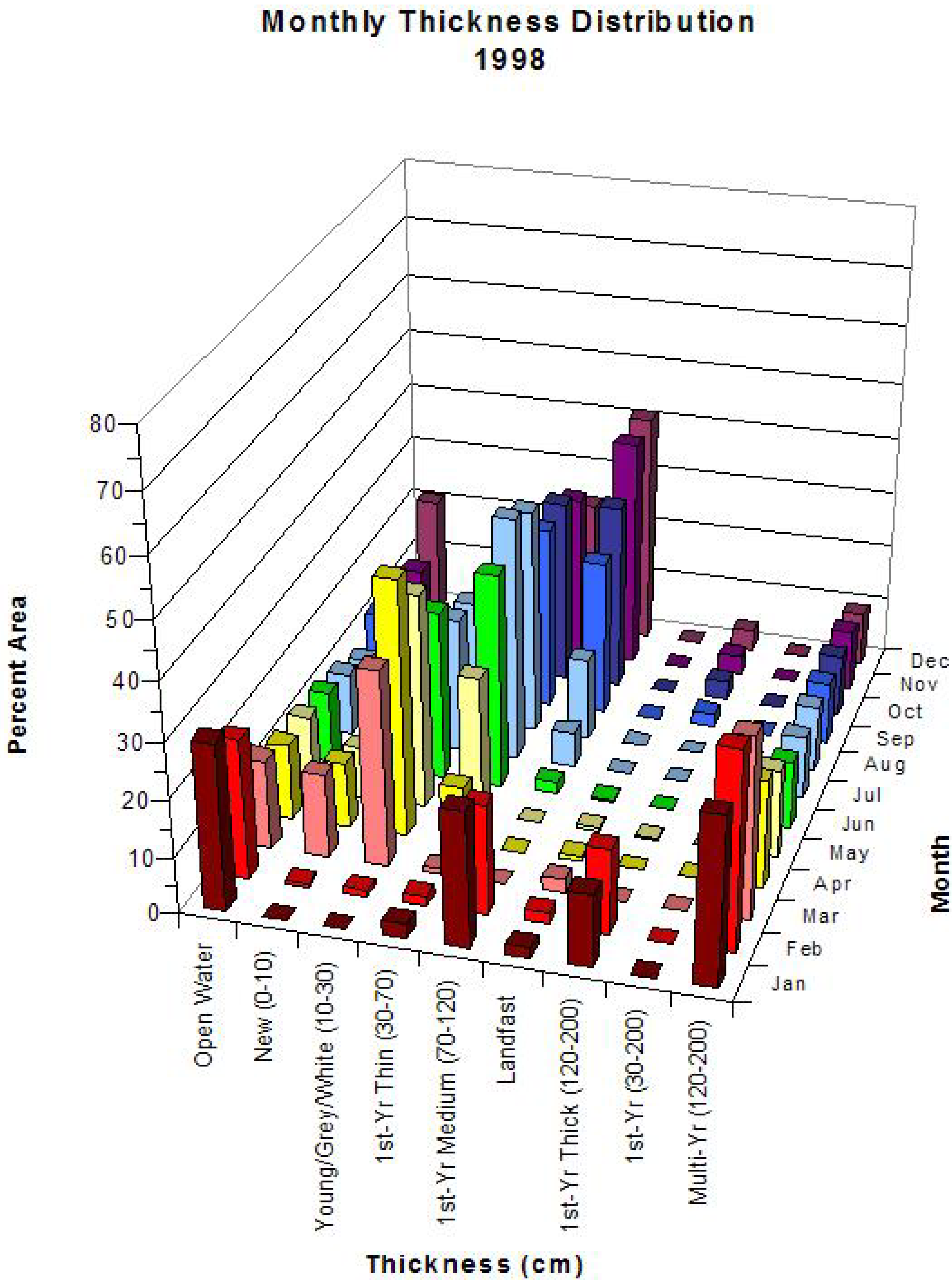

Figure 12. Monthly sea-ice thickness distribution for the Ross Sea in 1998.

Summary

This paper discusses the use of ArcGIS in the analysis of sea-ice thickness in the Ross Sea that is part of a larger NSF project. A continental-scale dataset with sea-ice information is compared with in situ ship-based observations to ascertain its quality for monitoring sea-ice thickness and mass balance changes in the Southern Ocean. The extent and variability of sea-ice

thickness is investigated in 1995 and 1998. Research is ongoing to analyze sea-ice extent, thickness and mass balance in the Ross Sea from 1995 through 2000.

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Author Information Tracy L. DeLiberty, Department of Geography, Pearson Hall 216, University of Delaware, Newark, Delaware 19716, Telephone 302-831-4084, Fax 302-831-6654, tracyd@udel.edu.

Cathleen A. Geiger, Cold Regions Research and Engineering Laboratory, 72 Lyme Road, Hanover, New Hampshire 03755, Telephone 603-646-4851, Fax 603-646-4644, cathleen.a.geiger@erdc.usace.army.mil.

Mary D. Lemcke, Department of Geography, Pearson Hall 216, University of Delaware, Newark, Delaware 19716, Telephone 302-831-2294, Fax 302-831-6654, bigmar@udel.edu.