Sea Ice Index: Interpretation Resources for Sea Ice Trends and Anomalies

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1 INTRODUCTION

To help users interpret the images and figures correctly, this document discusses the variability of sea ice, the applicability of statistical methods for trend detection, and the validity of passive microwave images of sea ice. See the section 10 References for further reading. We emphasize the Northern Hemisphere because of the relative abundance of reference materials on trends in arctic sea ice. Note that information on ice extent and concentration tells us nothing about the total volume of ice or ice mass balance - for that one needs ice thickness information as well (see Rothrock et al., 1999). Changes in global sea ice are often discussed in connection with climate change. For information on how sea ice and other cryospheric parameters respond to climate change, see State of the Cryosphere. To review other sea ice products at the National Snow and Ice Data Center (NSIDC), see Sea Ice Products at NSIDC.

Sea ice concentration can be estimated from brightness temperature data because sea ice and water have differing passive microwave signatures. Water has a highly polarized signature within a certain frequency band (that is, its brightness temperature in the vertical channel is higher than that in the horizontal), while sea ice does not. Most algorithms use some form of a polarization ratio and a mixing diagram with brightness temperature tie points to estimate the concentration of sea ice within the field of view of the sensor. The algorithms we use for the Sea Ice Index use the 19 GHz V, 19 GHz H, and 37 GHz V SSM/I channels, and the 18 GHz V, 18 GHz H, and 37 GHz V SMMR channels. The -3dB footprint of the 19 GHz SSM/I passive microwave channel is 69 km x 43 km; the 37 GHz is 37 km x 29 km. For SMMR, the 18 GHz channel has a 55 x 41 km footprint, and the 37 has a 27 x 18 km footprint.

More information on platform orbits, the SMMR instrument, and SSM/I instruments (F8, F11, and the current instrument, F13) can be found in Sea Ice Concentrations from Nimbus-7 SSMR and DMSP SSM/I Passive Microwave Data. A good introduction to characterizing sea ice with passive microwave data is Eppler et al. (1992) and Steffen et al. (1992). A good reference for understanding SSM/I sensor geometry and calibration considerations is Hollinger et al. (1990).

2 VARIABILITY

In the Northern Hemisphere, sea ice reaches an annual minimum extent in September, and maximum extent in February or (usually) March, although there may be regional variations. In the Barents Sea, for example, minimum ice extent consistently occurred in August over a 21-year time span (Parkinson and Cavalieri, 2002).

Sea ice extent varies as the sea ice edge responds to wind and ice growth or melt. Kimura and Wakatsuchi (2001) found that wind driven ice motion is the mechanism behind most of the variation of ice extent in the Barents Sea, Bering Sea, and Sea of Okhotsk. Variation of ice extent in the

Greenland Sea and Labrador Sea is more controlled by oceanographic factors, including the location of a thermal front in the Labrador Sea and rapid ice melting in the Greenland Sea. While their study focused on daily variations, Kimura and Wakatsuchi used monthly mean ice concentration data to infer that interannual variations in ice extent are controlled by the same mechanisms.

Interannual variability in extent is large: for example, a record minimum in September of 1995 was followed by very high extent the next year. Globally, the annual variation of sea ice area is about 37 percent of the mean (Gloersen et al. 1999). Because of this, it is difficult to infer long-term trends from short observational records, or to deduce the influence of possible natural oscillations in ice extent.

The great variability in sea ice extent is especially noticeable in maps depicting the frequency of occurrence of sea ice. The frequency of occurrence in longer data records, such as the Goddard Space Flight Center's Sea Ice Concentrations from Nimbus-7 SSMR and DMSP SSM/I Passive Microwave Data (GSFC series) passive microwave data set, is greater than zero and less than 100 percent of the time in a broad ring around the central pack. The width of this ring reflects changes in the sea ice edge position over the span of the data record. Parkinson's analysis (2000) has figures displaying these areas based on the 1979-1996 record. The Environmental Working Group Joint U.S.-Russian Arctic Sea Ice Atlas, a data product of digital ice charts from the U.S. National Ice Center and the Russian Arctic and Antarctic Research Institute, has frequency of occurrence figures based on 1972-1990 operational sea ice charts. Refer to Figures 1 and 2.

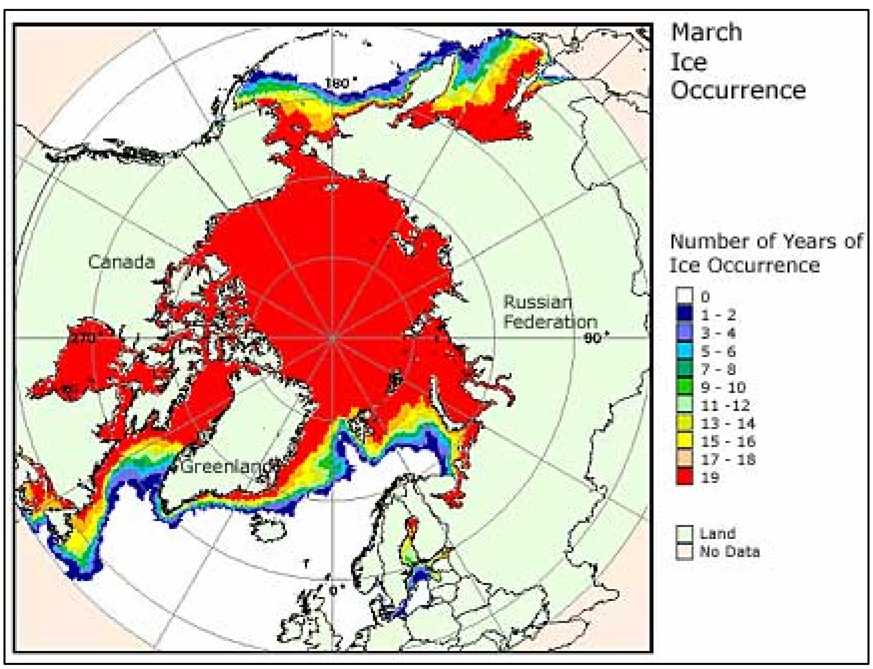

Figure 1. Frequency of ice occurrence in March, the month of maximum ice extent, from sea ice charts over 1972-1990 (Courtesy of the Environmental Working Group Joint U.S.-Russian Arctic Sea Ice Atlas).

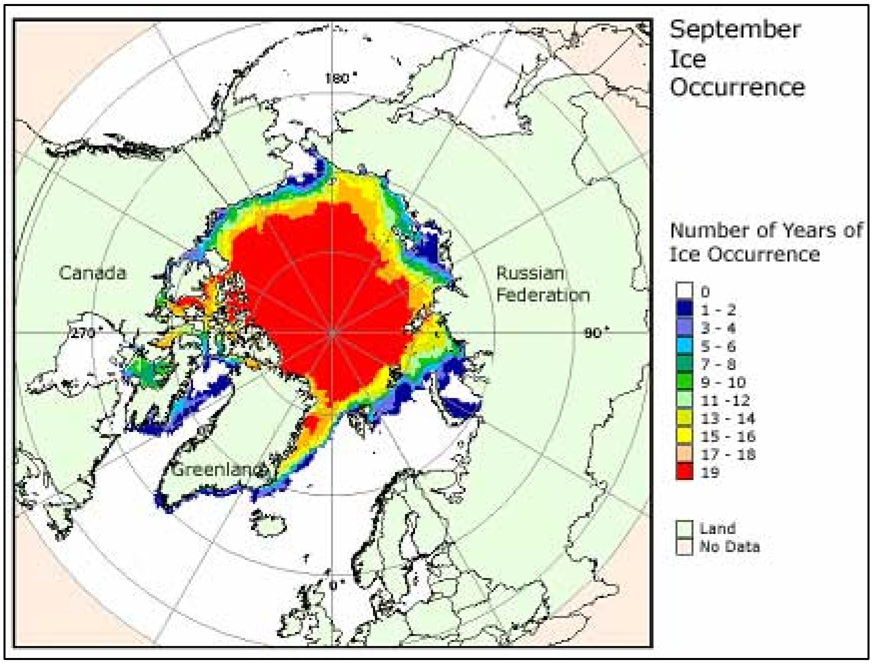

Figure 2. Frequency of ice occurrence in September, the month of minimum ice extent, from sea ice charts over 1972-1990 (Courtesy of the Environmental Working Group Joint U.S.-Russian Arctic Sea Ice Atlas).

3 LINEAR REGRESSION FOR TREND ANALYSIS: ASSUMPTIONS AND LIMITATIONS

Derived trends answer the questions, "Is the concentration of sea ice decreasing in this region?" or "Is the portion of the polar ocean covered with ice decreasing with time?" These questions imply a desire to predict what will happen, in addition to showing what has happened.

Linear regression, or fitting a line to a series of data points and finding the slope of that line, is the method used here to help answer these questions. Understanding the limitations of linear regression will help phrase the answers to these questions carefully and precisely. For example, linear regression assumes, obviously, a linear relation between ice and time. But what if ice is varying in a cyclical or oscillatory fashion? A linear model won't describe changes in ice conditions well, and if our time series is not long enough to capture several cycles we cannot know that the model is inappropriate. What about anomalous years that produce outliers in ice extent? The year 1995, for example, had the lowest September ice extent ever, until 2002. If a trend in September extent over 1979-1999 is calculated without including this year, ice extent is decreasing at -2.7 percent per decade. Refer to Figure 3. If 1995 is included, the result is -3.2 percent per decade. Refer to Figure 4. Obviously, that single year in a 21-year series has great influence. There are methods for identifying outliers and mitigating their influence in linear regression, but removing such outliers is probably inappropriate since they result from the same forcing mechanisms that drive ice conditions in normal years.

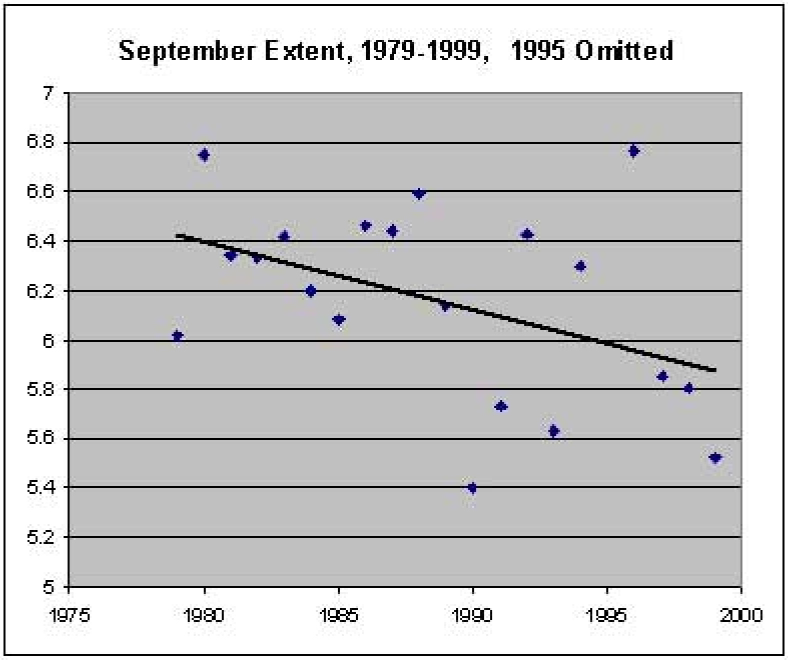

Figure 3. September Ice Extent Chart, 1979-1999, 1995 Omitted.

The y-axis is millions of sq km

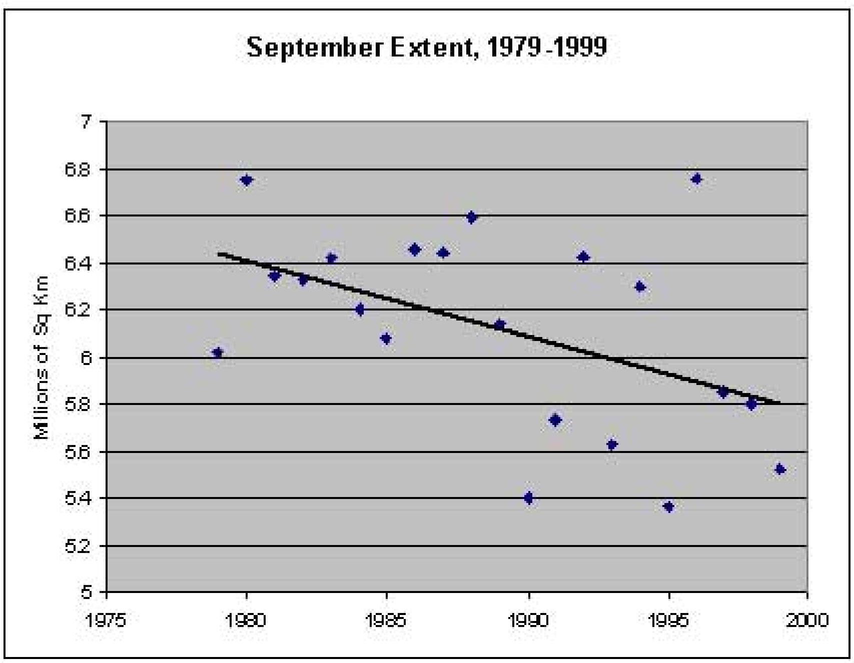

Figure 4. September Ice Extent Chart, 1979-1999

In linear regression, the model $y = B_0 + B_1 x + E$ is applied.

Where:

Variable	Description
B_0	intercept parameters
B_1	slope parameters
x	is known (the independent variable)
E	random error

We postulate that x (month in a time series of years) determines y (ice extent or concentration) and based on measurements of y, we solve for B_0 and B_1 to learn at what rate ice is changing over time. However, in reality, we know that it is not time that is determining ice conditions but rather forcing by heat flux and advection by wind. The predicted value of y for a given x is

$\hat{y} = \hat{B}_0 + \hat{B}_1 x$. To fit a trend line to a series of points, that is to find B_0 and B_1, the errors in the sum of the squared predicted values of y (the residuals, or $y - \hat{y}$) are minimized. If scatter in the series is large, the sum of squared errors will be large, and relatively little of the variability in y is explained by x. Another way to say this is that if little variability is explained by time, time is not a good predictor of how ice changes.

The sum of squared errors, or more specifically the mean squared error, which is the sum of squared errors over the number of data points minus two, is used in inferences concerning the statistical validity and the confidence interval of B_1, or slope. The Sea Ice Index images of trends in concentration show trends for which we reject the null hypothesis that the slope is equal to zero with 95 percent confidence.

The plots of trends in the extent anomalies include a 95 percent confidence interval for slope. The interval indicates that we are 95 percent confident that the true slope or trend line is between the values given. If the interval includes zero, we cannot reject the hypothesis that there is no trend in extent for that month.

Note that while a trend may be statistically significant, a wide confidence interval signals considerable uncertainty in the relationship between passing time and ice conditions. Ice extent shows great temporal variability that works against a tight linear relationship.

Is a simple linear regression model the right tool for modeling changes in sea ice? Almost certainly not, because atmospheric forcing appears to be oscillatory. If we remember that we are not modeling ice behavior or predicting ice conditions, but are simply quantifying changes that have taken place over the period of record, linear regression for trend analysis is useful.

4 CONCENTRATION TRENDS

Most of the Arctic Ocean is white in the monthly mean trend images. That is, there is no significant trend in sea ice concentration. One reason for this is because we are using the GSFC series data, extended with the Near Real-Time SSM/I Polar Gridded Sea Ice Concentrations (NRTSI) data set. Less than 20 data points are in the series, making the confidence band for the derived slope larger than it would be with a longer time series. When trends are derived using the longer time series (results not shown), trends are significant over a larger area, although most of the Arctic Ocean is without a significant trend even with the longer series.

A comparison of trends using the GSFC series and the NRTSI series illustrates how results can vary depending on the starting and ending point used. The longer GSFC series data shows the Sea of Okhotsk to have a strongly negative trend in concentration for January to April, while the shorter NRTSI series data shows a positive trend. Gloersen et al. (1999) detail a number of regions for which local trends are different when calculated using an 18.2- versus an 8.8-year time series, and attribute these inconsistencies in trends to long-term oscillations in the ice pack.

While the images of concentration trends can be interesting, the short time series and relatively small and scattered areas over which trends are significant cautions against drawing conclusions about future concentrations based on these trends.

5 ANOMALIES

Anomalies in all but the central arctic pack reflect, for the most part, changes in ice extent rather than changes in concentration. For example, off Greenland in the winter anomaly images for 2002, the tongue-shaped Odden feature appears as a negative anomaly area, because no Odden occurred this year. Refer to Figure 5. In many winters, cold surface water in the Jan Mayen Current causes the Odden to grow eastward from about 72 to 74 degrees North. Refer to the How Does Arctic Sea Ice Form and Decay Web page. The Odden exhibits considerable interannual variability (Comiso et al. 2001). Similarly, the large negative anomalies north of the Alaskan and Siberian coasts in September 2002 reflect the record retreat of the ice edge that summer (Serreze et al. 2003). Refer to Figure 6.

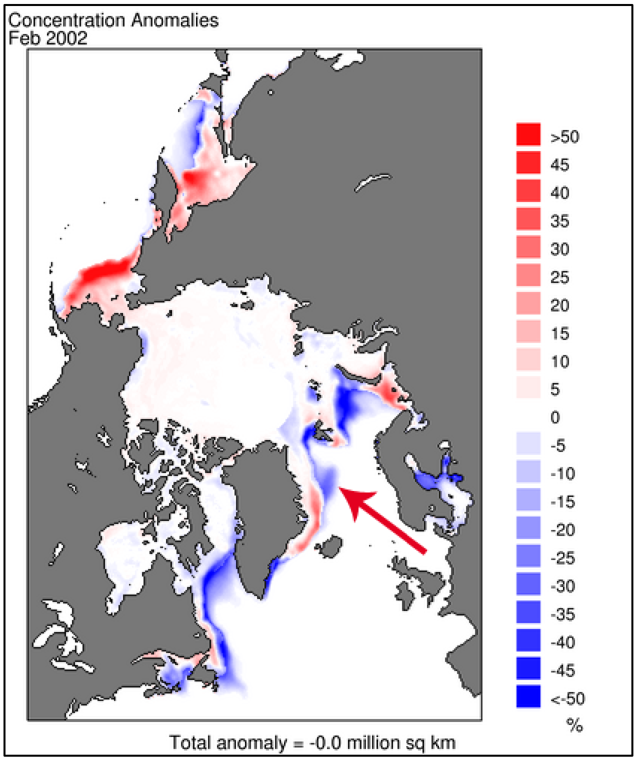

Figure 5. The red arrow indicates the Odden-shaped ice anomaly.

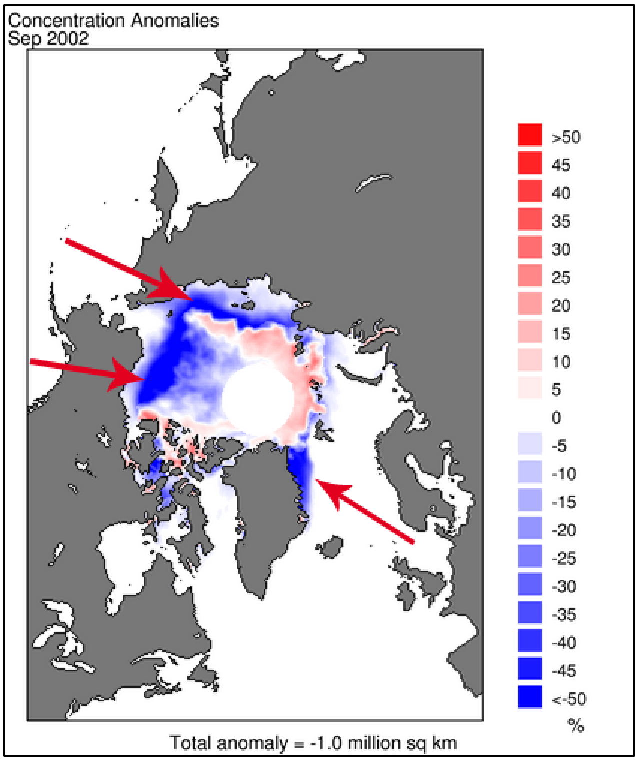

Figure 6. The red arrows indicate negative anomalies covering much of the East Siberian, Beaufort, and East Greenland Seas, the result of record minimum ice extent in the summer of 2002.

6 EXTENT TRENDS

Trends in total sea ice extent, because they are based on the relatively reliable measurement of the sea ice edge location from passive microwave data, probably relay more useful information than do the images of trends and anomalies in concentration. Parkinson and Cavalieri (2002) explore regional and seasonal variability in trends in sea ice extent with plots of extent trends derived from a 21-year passive microwave data set. When the Northern Hemisphere is taken as a whole, sea ice extent is decreasing at a rate of -2.7 ± 0.5 percent per decade. The rate of decline in summer (-4.9 ± 1.5 percent) is considerably greater than that for winter (-1.8 ± 0.6 percent).

As with concentration trends, it is important to remember that the value of a sea ice extent trend and even its sign (usually expressed in the literature as percentage change in ice extent per decade) may depend on the start and end point of the time series. For example, Parkinson et al. (1999) find a reduction in Arctic Ocean ice extent from November 1978 through December 1996, but an increase when only 1990 to 1996 is considered.

As noted earlier, simple linear regression is not the best tool for modeling changes in sea ice. Linear regression assumes that data points in a time series are independent samples, when in fact sea ice exhibits persistence: conditions in any given month usually depend on conditions in the previous month. An autoregressive model, in which observations are modeled as a function of the value of prior observations, would be more appropriate. However, Piwowar and LeDrew (2001) tested this assumption using passive microwave data and found that autoregressive models are valid for only about 60 percent of the Arctic. They hypothesize that thermal inertia of the sea ice pack dominates in these regions, while elsewhere, factors such as changing weather patterns increase variability. Vinnikov et al. (2002) estimate that the auto correlation time scale of observed daily sea ice extent is about 50 days. Mean monthly sea ice extents, then, are probably independent, although we cannot rule out periodicity on a longer time scale.

Vinnikov et al. (2002) deduce seasonal cycles in sea ice extent trends from daily passive microwave data using harmonic analysis. Unlike linear regression, their method does not assume that the population of observations is stationary. Results are consistent with other more traditional analyses, that is, monthly sea ice extent trends in the Northern Hemisphere have negative values for all 12 months, based on a 20-year data record.

7 VALIDATION

There are a number of algorithms in use that convert channel brightness temperatures to sea ice concentration. All perform slightly differently under varying weather and sea ice conditions. Relatively few papers were published that compare algorithms or compare results with validation data. These include Comiso and Steffen (2001), Meier et al. (2001), Steffen and Schweiger (1991) and Emery et al. (1994). The Sea Ice Index is based on the NASA Team algorithm (NT2) (Cavalieri et al. 1984) because the NRTSI product uses this algorithm.

It is possible to make some generalizations about the accuracy of passive microwave sea ice concentrations. Gloerson and Campbell (1991) estimate that sea ice concentration retrievals are accurate to within 5-9 percent, depending on the sea ice being imaged. Passive microwave algorithms generally cannot detect thin sea ice reliably (Cavalieri 1994). Based on comparisons with analyses of synthetic aperture radar data, passive microwave overestimates open water by 3 to 5 times in winter (Kwok 2002). The winter coverage of open water is only about 0.3 percent. New openings in the ice, that appear as linear leads, freeze over almost immediately.

In summer, passive microwave overestimates open water by a larger amount, as the instrument cannot distinguish open water between ice floes with melt ponds on the floes, and other factors such as the ice-snow interface come into play (Comiso and Kwok 1996) and (Fetterer and Untersteiner 1998). This makes it difficult to interpret trends and anomalies for the summer months. The statistically significant negative trend in the Beaufort Sea in June and July, for example, may reflect a real trend towards more open water, but is also likely to reflect a trend in sea ice surface conditions that masquerades as a trend in sea ice concentration.

Probably the best validation data for passive microwave sea ice retrievals are charts from operational ice centers. These charts are drawn by analysts based on satellite data from a number of sources as well as, in some cases, ship or aerial surveys. A study based on digital versions of the U.S. National Ice Center's (NIC) charts covering the Arctic every week from 1972-1994 (Partington et al. 2003), shows that NIC charts consistently report about 4 percent more ice per unit area than passive microwave retrievals from the NT2 algorithm. This holds for November through May. Beginning in June, the difference rises to about 23 percent, and falls off gradually over the summer and into fall freeze-up. The difference after freeze-up (which begins in September over most of the Arctic) is probably due to the insensitivity of the passive microwave algorithm to thin sea ice. Both chart data and passive microwave data show a negative trend in integrated arctic-wide concentration over the period 1979-1994. The difference between the passive microwave and chart trends is statistically significant only in the summer, where it is about 2 percent per decade steeper in passive microwave data.

A comparison of ice-covered area from the NT2 algorithm with 18 years of Canadian Ice Service charts showed that passive microwave data markedly underestimates sea ice area by 30 to 40 percent during spring melt and fall freeze-up, for the Hudson Bay and East Coast regions. There is considerable scatter in the differences rather than a consistent pattern (Agnew and Howell 2002a, 2002b). The difference between chart and passive microwave-derived ice areas is greater for the Canadian charts than the U.S. charts. This is likely a reflection of the fact that the U.S. National Ice Center uses passive microwave when other data are not available, which is often the case for the central Arctic and other remote areas, while the Canadian Ice Service rarely uses passive microwave data, relying instead on airborne and satellite radar, satellite optical, and visual observations for charts of the Canadian Arctic. These methods detect thin ice, lower concentrations of ice, and flooded ice much better than passive microwave data allows (personal communication, J. Falkingham, Chief of Operations, Canadian Ice Service, December 2002).

Spot checks of the sea ice edge position using a 15 percent concentration cutoff against NIC ice charts show that when there is a broad, diffuse ice edge, the NRTSI and GSFC products sometimes do not detect sea ice where the concentration can be as high as 60 percent. When the sea ice edge is more compact, the 15 percent concentration cutoff reflects its location fairly well. The large footprint of the 19 GHz channel means that a compact sea ice edge is smeared out in passive microwave imagery.

A study comparing passive microwave sea ice concentration data with approximately 1 km resolution imagery from the Advanced Very High Resolution Radiometer (Meier 2005) focuses on the sea ice edge. Four SSM/I algorithms are used. The work illustrates how algorithms often underestimate concentration. The NASA Team underestimates concentration by about 10 percent on average, and by much more in some circumstances.

Newer algorithms were developed that perform better than the NT2 algorithm. An enhanced version of the NT2 algorithm incorporates the SSM/I 85 GHz channel and applies a forward-radiative transfer model to correct for weather effects that are exacerbated by use of the 85 GHz channel. This algorithm is the standard algorithm for arctic sea ice concentration retrievals with the AMSR-E instrument (Markus and Dokken 2002).

We have considered using one of the newer algorithms for the Sea Ice Index, but this would require research and reprocessing in order to ensure that the record is consistent over the entire time series. The SMMR instrument did not include a high frequency channel like that used in newer SSM/I and AMSR-E sea ice algorithms.

8 OTHER DATA SOURCES

Scientists often use passive microwave data to characterize long-term changes in sea ice cover because of the length, frequent coverage, and relative consistency of the data record. Other data sources are available. The Radarsat Geophysical Processing System produces sea ice motion, deformation, and estimates of thickness from synthetic aperture radar imagery. Digital versions of the U.S. National Ice Center's charts and the Russian Arctic and Antarctic Research Institute's charts are available from NSIDC's Environmental Working Group Joint U.S.-Russian Arctic Sea Ice Atlas data set. The Global Digital Sea Ice Data Bank project is working to make other digital chart data available. Operational ice services are the best source for timely and accurate regional ice conditions.

A summary of all sea ice products distributed by NSIDC is available.

9 REFERENCES ON TRENDS IN ARCTIC ICE

A number of references provide context for trends and anomalies by permitting them to be seen as part of a longer climatological record, or by looking at the causes behind ice conditions and trends. Only a sample are mentioned here.

Maslanik et al. (1996) attribute the large negative summer ice extent anomalies of recent years to an increase in cyclonic activity, which advects the ice northward while at the same time increasing the rate of melting. More detailed analyses of specific years are given in Serreze et al. 2003, Serreze et al. (1995) and Maslanik et al. (1999).

Authors have placed variability of sea ice in the context of long-term and large-scale atmospheric variability. One mode of this variability is the Arctic Oscillation (AO) (Thompson and Wallace 1998). The positive mode of the AO is characterized by lower than normal atmospheric pressures over the Arctic Ocean, and a weakening of the anticyclonic (clockwise) circulation of the Beaufort Gyre. Stronger winds and higher air temperatures are associated with the positive mode of the AO. Positive AO winters may precondition the sea ice pack for reductions in summer extent and concentration, as weaker anticyclonic sea ice circulation results in greater ice divergence and therefore more thin sea ice, and strong winds move sea ice away from the coast (Rigor et al. 2002). In the spring, the thin ice melts quickly. Since the 1980s, the positive mode of the AO has tended to dominate, and this has played a part in recent record sea ice extent minimums.

Polyakov and Johnson (2000) argue that another mode, a low frequency oscillation with a time scale of 60 to 80 years, is also contributing to thinning sea ice, and that the large amplitude of natural variability in the Arctic due to oscillatory modes makes trend detection difficult. Vinje (2001), using a more than 100-year record of sea ice extent in the Nordic Seas, finds that sea ice extent has been reduced by about 30 percent, but concludes that this is within the range of natural variability, and suggests that sea ice conditions are still recovering from sea ice expansion in the Little Ice Age. The record shows oscillations with a period of 12 to 14 years. Because of these oscillations, less than 3 percent of the variance in Nordic sea ice extent with respect to time can be explained with a 30 year or shorter data set.

Comiso (2002) uses the annual summer minimum sea ice extent as a proxy for the extent of the perennial ice pack, since the ice that is left at the end of summer is composed for the most part of multiyear floes. Using passive microwave data from 1978 to 2000, he finds that the extent of this thicker sea ice is declining at a rate of 6.4 ± 2.2 percent per decade, with a strong correlation (-0.77 correlation coefficient) between declining extent and rising summertime surface air temperatures. Comiso notes that a reversal of this trend is possible under a change in the atmospheric circulation regime, for example under cycling of the AO. However the magnitude of the decline and consideration of sea ice feedback mechanisms leads him to conclude that an irreversible change in arctic sea ice is suggested in the absence of near-term recovery of the perennial pack.

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