

IMAGE TREND ANALYSIS

In an analysis of twenty-five years of ice extent anomaly data compiled largely from governmental observational programs covering the period 1953 to 1977, Walsh and Johnson (1979) found a statistically significant increasing trend in overall Arctic ice extent of 3140 km² per year. They concluded that this net positive trend was influenced the most by increased iciness in the Bering Sea, Baffin Bay, Davis Strait, and East Greenland Sea regions. Their analysis also revealed that the ice cover over the Barents Sea was apparently decreasing. It is clear from this study, and others, that there appears to be regional and hemispheric trends in polar ice conditions which may be related to climate change.

In this report, the approach used by Walsh and Johnson (1979), and others (e.g., Lemke *et al.*, 1980; Chapman and Walsh, 1993; Gloersen *et al.*, 1993), is extended into the hypertemporal image analysis domain. Like Walsh and Johnson, the present application uses linear regression fit to time series of sea ice data. Unlike Walsh and Johnson's (and others') work, however, this study examines trends in ice concentration at 25 km (nominal) intervals across the Arctic (their analysis measured the trend in ice extent for the entire Arctic as a whole). The intent is to determine the linear trends in Arctic ice concentrations between 1978 and 1987 while establishing image trend analysis as a viable tool for climate change analysis.

1 IMAGE TREND ANALYSIS

Image trend analysis is a technique which has been applied to image pairs to differentiate between actual change and predicted change (Singh, 1989; Eastman and McKendry, 1991). The procedure is initiated by considering pixel values from the image at time t to be samples of the independent variable and pixels from the time $t+I$ image as samples of the dependent variable. A regression line is then fit to the data points. The computed slope and intercept values are applied on a per-pixel basis to the first image to produce a predicted image for time $t+I$. The actual and predicted time $t+I$ images are then differenced or ratioed to isolate the changed areas.

The image trend analysis technique is particularly effective when it is reasonable to expect the two images to have the same mean and variance (as in two images acquired by the same sensor exactly one year apart) or to account for differences in the mean and variance between the two dates (as might result from changes in atmospheric or illumination conditions) (Singh, 1989; Eastman and McKendry, 1991). It is limited to pairwise comparisons, however.

For hypertemporal analyses, this concept can be modified to work between many images by treating time as the independent variable and pixel value (sea ice concentrations, in this case) as the dependent variable, *on a per-pixel basis*. One way to envisage this is to "slice open" a hypertemporal image stack to reveal a temporal face, as in Figure 1. Per-pixel time series are extracted by recording the pixel values along a vertical traverse of the image stack. Four such plots from (arbitrary) sample locations indicated by the four vertical black lines extending along the temporal face of Figure 1 are drawn in Figure 2. The heavy ice summers and light ice winters of 1984-85 are clearly reflected in the Beaufort Sea (Pixel 70) and Barents Sea (Pixel 210) graphs, respectively. From an examination of these and other such plots, it is evident that different locations can experience quite different variations in ice conditions.

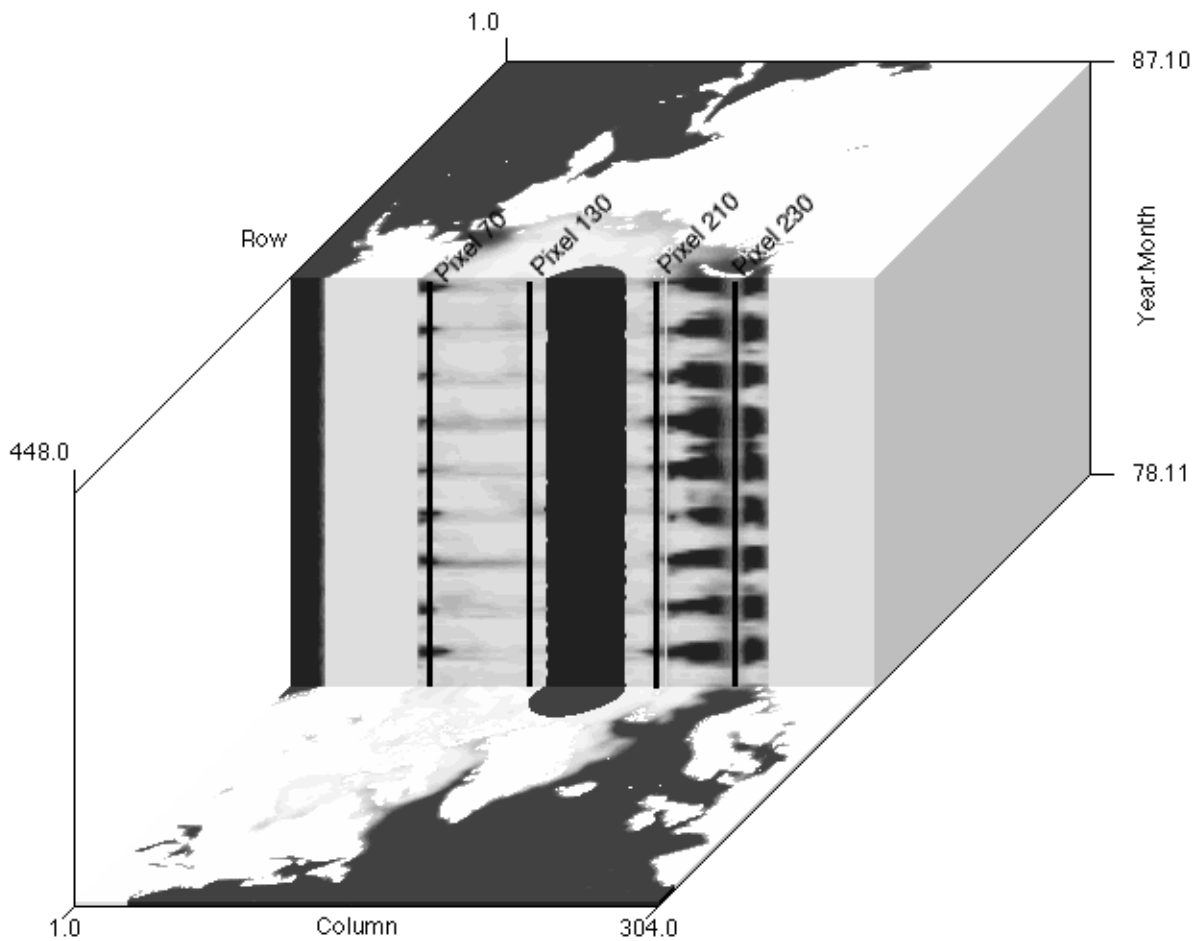


Figure 1: Sample Locations for Trend Analysis
Samples were taken from the temporal face exposed along line 224.

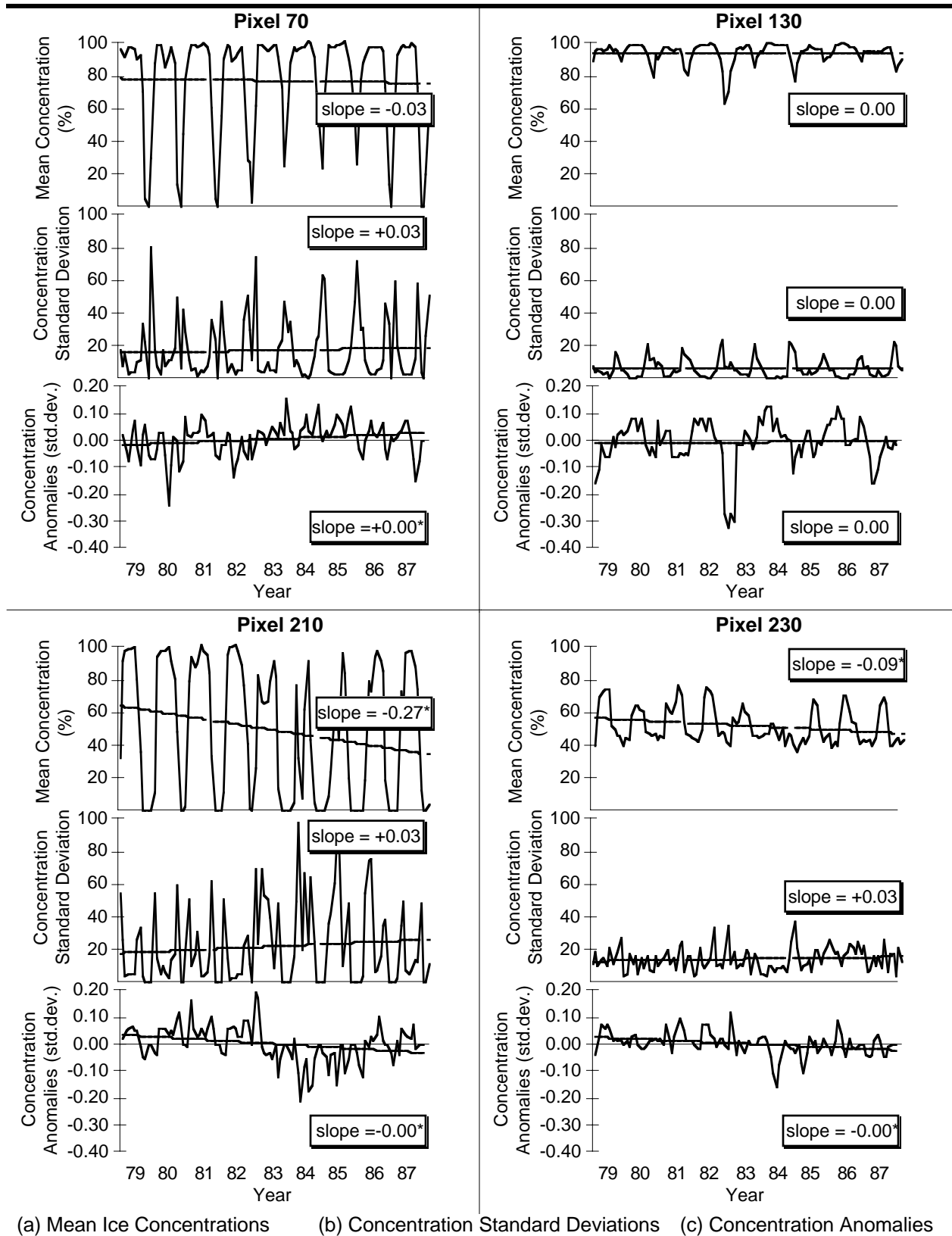


Figure 2: Sample Plots of Monthly Sea Ice Concentration Linear Regression Series
 * - slope is statistically significant at the 95% level.

An examination of the plots in Figure 2 raises the question: Has there been an overall change in ice concentration over the nine-year period of record? One method of searching for overall trends is by examining the slope of the regression line. Figure 2 shows that, for the four sample series plotted, there appears to be a decreasing amount of ice in the Barents Sea (Pixel 210) while the ice conditions are more stable in the Beaufort Sea (Pixel 70). A *t*-test was used to test the hypothesis that these slopes were not significantly different from 0 (Johnson, 1980). The negative slopes at Pixels 210 and 230 are statistically significant at the 95% level; the mean trends at Pixels 70 and 130 are not significant.

Following this approach, a linear regression was fit to the time series for every image pixel in the mean image stack and the slope of each trend line was assigned to the corresponding pixel in a new image. Figure 3a identifies the regions of significant trends in mean ice concentrations during the SMMR period.

It should be noted at this point that one of the basic assumptions of linear regression has been violated in this approach: that the data are not autocorrelated. Clearly, the monthly mean sea ice concentrations include a significant amount of autocorrelation in the seasonal signal. Consequently, the trend analysis was repeated using the normalized anomaly stack. Recall that the anomaly data set was created by subtracting each monthly ice concentration from the nine-year mean value for the same month. This method has the effect of "deseasonalizing" a time series (Hipel and McLeod, 1994). Regions of statistically significant anomaly trends are highlighted in Figure 3b.

It has been suggested that climate change may be more evident as changes in variability than as changes in mean (Coughlan and Nyenzi, 1990; Katz and Brown, 1992). One measure of variability retrievable from the SMMR data are trends in the monthly standard deviation of sea ice concentrations. Figure 3c shows statistically significant trends in monthly standard deviations of ice concentrations. There is some seasonal autocorrelation remaining in these data, however.

2 INTERPRETATION

A visual review of the regression trends in Figure 3 highlights seven regions where significant temporal processes appear to have affected the sea ice concentrations over the nine year SMMR period. The ice conditions from locations in these regions are examined in this section. For comparison purposes, one additional region was selected from the East Siberian Sea where no significant trends appear to have been present. The location of all eight regions discussed here are identified in Figure 4.

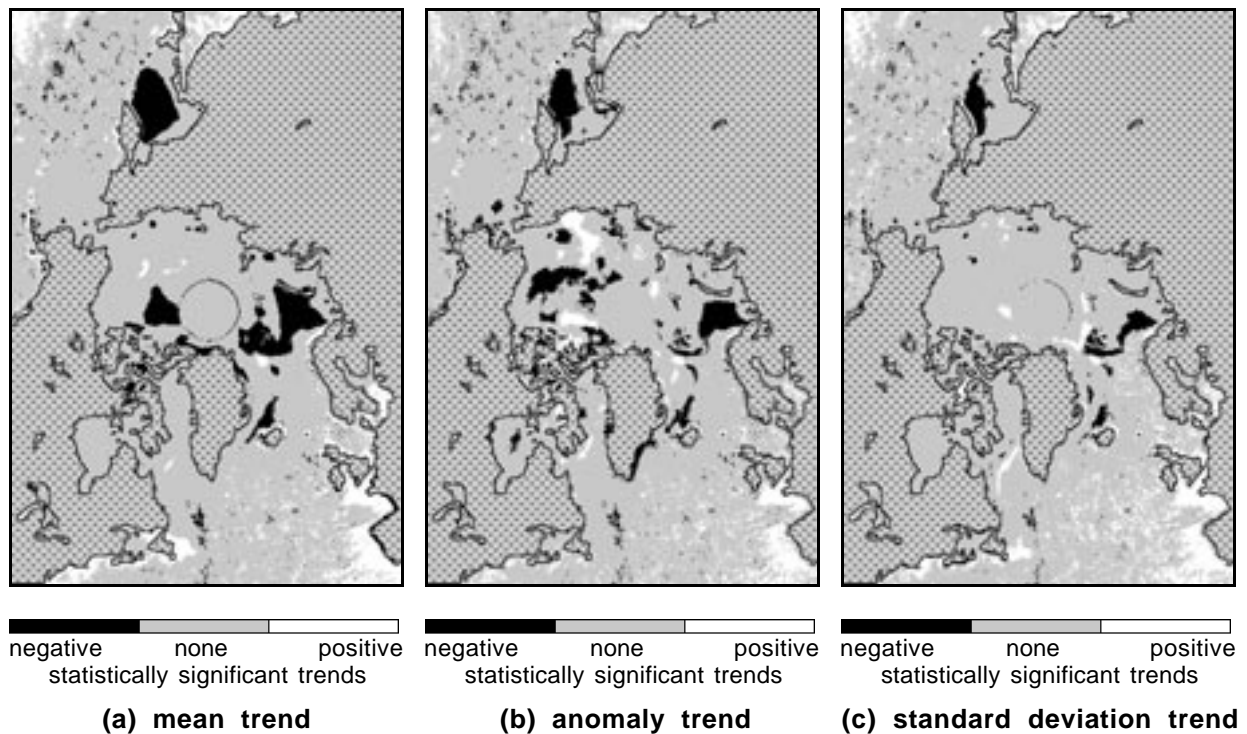


Figure 3: Significant Arctic Ice Concentration Trends: 1978-1987
Statistical significance is specified at the 95% confidence level. Spurious "significant" pixels in sub-polar regions are due to land and atmospheric contamination of the SMMR signal.

One time series from a sample location in each of the eight regions was extracted from the mean, standard deviation, and anomaly magnitude stacks to assist in the explanation of the mapped trends. These plots are shown in Figure 5. Time series plots of the mean sea ice concentrations and their standard deviations are all scaled between 0 and 100%; anomaly magnitudes range between 0 and 2 standard deviations. In particular, any sea ice anomaly which is greater than 2 standard deviations can be considered statistically significant at the 95% confidence level.

2.1 Barents Sea

The greatest trends in ice concentrations for the nine year SMMR period are negative and occur in the Barents Sea (Figure 3). In these regions, the calculated trends indicate a statistically significant decrease in mean ice concentrations of 0.4% per month. An examination of the time series profiles of the mean concentrations for the Barents Sea (Figure 5) shows a four year period of above average ice conditions followed by low sea ice concentrations during the winters of 1983 through 1985. Although it appears as if more "normal" conditions appear to return in 1986 and

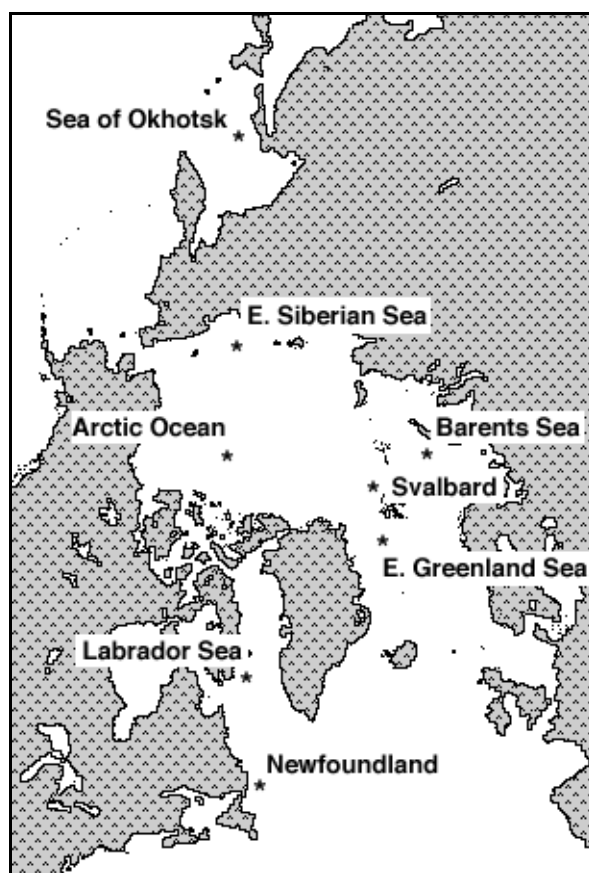


Figure 4: Location Map for Trend Analysis Plots

1987, the peak winter concentrations in the last two years of the sequence are still 5% lower than the maximum concentrations between 1979 and 1982. This trend is also carried in a significant reduction in the size of the monthly anomalies toward the end of the measurement period. The ice cover in this region is extremely variable and no significant changes in that variability are evident from the data.

2.2 Svalbard

Like the Barents Sea, the Svalbard region is another location of strongly decreasing mean ice concentrations, with the trend line indicating a significant decrease of about 40% between 1978-87 (Figure 5). Unlike the Barents Sea, however, there are no statistically significant changes in anomaly magnitudes. The time series profiles for the Svalbard region show a general decrease

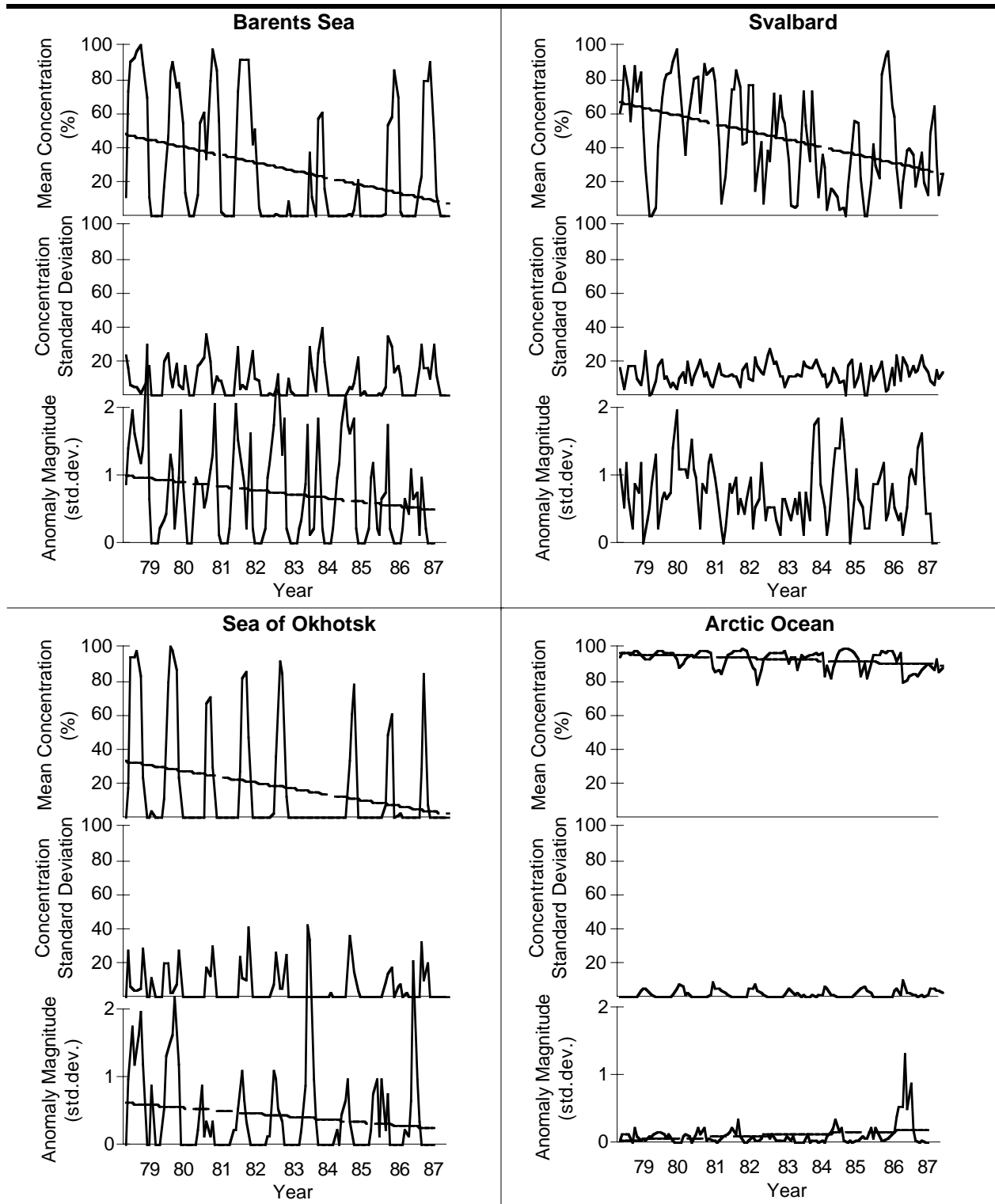


Figure 5: Time Series Plots and Significant Regression Lines for Eight Arctic Locations
Trend lines are plotted only where they are statistically significant at the 95% level.

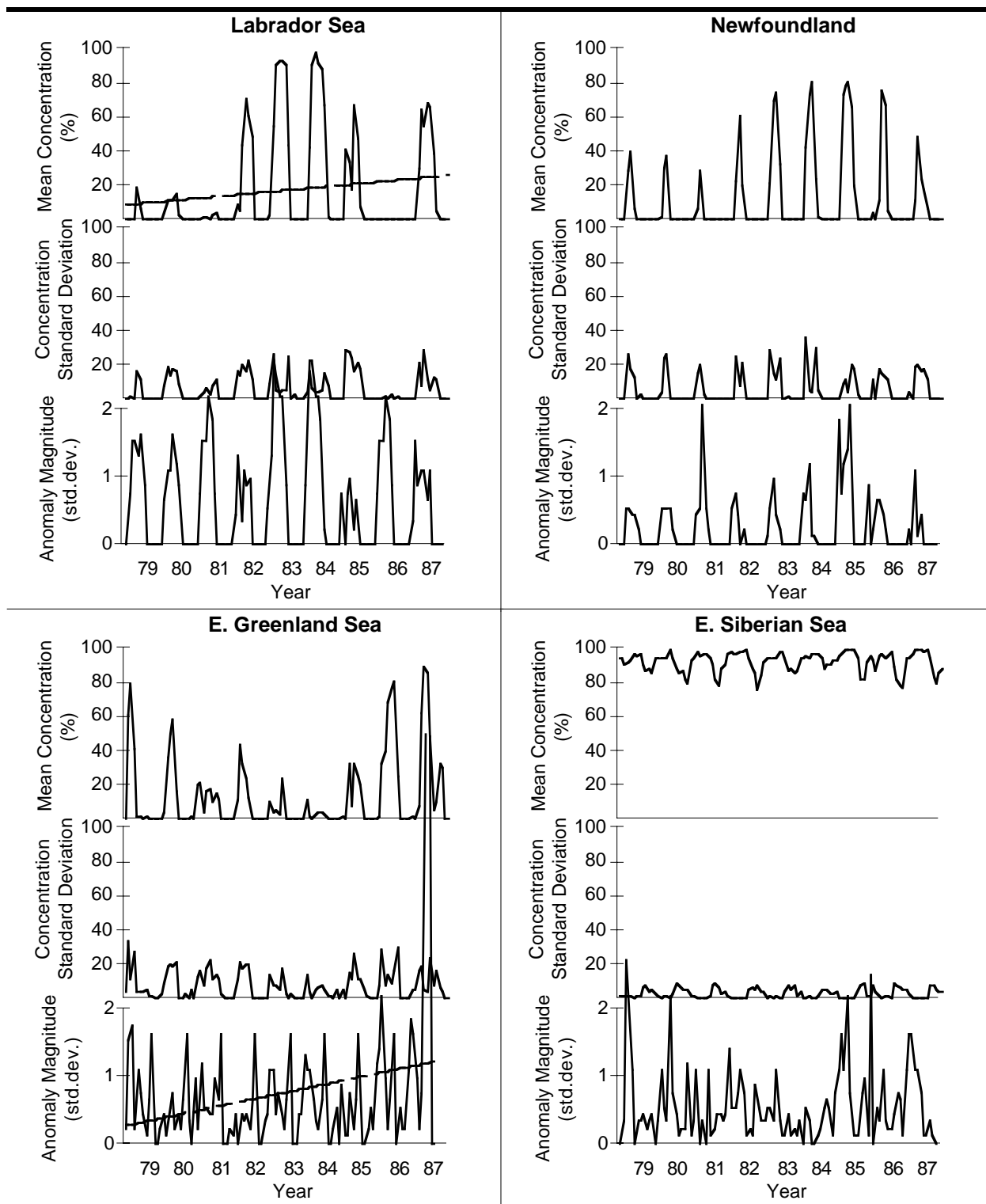


Figure 5: (cont.)

in ice concentrations and anomalies from 1980 through 1985. Interestingly, however, this period is immediately preceded by a time of very low ice concentrations (summer 1979) and terminated by very high concentrations (winter 1986). Since none of the monthly anomalies are greater than 2, any observed trends over the nine year period are perhaps due more to natural variation than shifts in the base ice concentration level.

2.3 Sea of Okhotsk

The Sea of Okhotsk is another region of widespread trends towards lower ice concentrations during the SMMR period, decreasing at a rate of about 0.3% per month. The time series plots (Figure 5) show a seasonal cycle of ice concentrations peaking in winter, with the region becoming ice-free early in summer. The Sea of Okhotsk experienced heavy ice conditions in excess of 90% during first two winters (1979-80), followed by three winters of ice concentrations around 80%. The three winters at the end of the time series (1985-87) had average ice concentrations of 70% although the brevity of the last winter measured is reflected in a strong anomaly. The cycle was notably interrupted during the winter of 1984 when the region remained completely free of ice resulting in another statistically significant ice anomaly. In spite of these strong anomalies in the second half of the period, there is still a statistically significant decrease in anomaly magnitude over the nine year period probably as a result of the shorter winter ice seasons at the end of the series. Shorter winters also mean longer ice-free periods, which are inherently less variable. The winter peaks in monthly standard deviations appear to be relatively constant over the nine year period and no trends are present.

2.4 Arctic Ocean

A significant negative trend in mean ice concentrations is evident in the central Arctic Ocean (Figure 3). A time series sampled from this region reveals that the central Arctic is generally characterized by very low monthly variation in ice concentrations (Figure 5). The downward trend for this location may be misleading, however, since it appears to be the result of a single negative anomaly at the end of the series (during the winter of 1987). This season of lower than normal ice concentrations also imposes a significant positive trend on the anomaly magnitude series. It is unlikely that these trends are climatically important since it appears that they have been caused by a singular deviation from the norm. If an anomaly of similar proportions had occurred in the middle of the time period, it would have had a negligible influence on the overall trends.

2.5 Labrador Sea

In contrast to the four regions of declining mean ice concentrations described above, only small pockets of increases are observable (Figure 3). The largest of these is found in the Labrador Sea, where regression slopes ranging up to +0.16% monthly suggest a net increase of 17% in ice concentrations between 1978 and 1987. This trend is not clear, however, from an examination of the corresponding time series plot (Figure 5). While the series does show an increase in winter ice concentrations from near 10% in 1979 through 1981 to over 90% in 1983 and 1984, the inconsistent fluctuation at the end of the time series suggests that these changes may be part of this region's natural variability. This is supported by the anomaly time series which indicates that, except for the winter peaks of 1983 and 1984, none of the anomalies are significant and there are no significant trends.

2.6 Newfoundland

Another region of higher mean concentrations is found off Newfoundland's eastern coast. Although much of this area of increased iciness is close enough to the Newfoundland landmass to make land contamination of the SMMR signal suspect, it remains part of a larger zone of elevated concentrations which supports its validity. Some parts of this area, further out from the coast, have a linear trend in mean sea ice concentrations of +0.10% per month. No significant trends are identified in the time series plots (Figure 5), although it is not hard to visualize that the peaks of this plot are components of a longer-scale oscillation, with a period of ten or eleven years. This may be the pattern of normal variation for this region. In fact, such an oscillation has been noted by Ikeda (1990a,b) and corroborated by Kelly *et al.* (1982) who find a statistically significant cycle of surface air temperatures in the Arctic with a period of about twelve years.

2.7 East Greenland Sea

A time series plot for a third region of increasing mean concentrations located in a small pocket of the East Greenland Sea is given in Figure 5. Just as in the Newfoundland Sea, annual changes in ice concentrations in this area may also be following a decadal-scale oscillation, with decreasing values to winter minima in 1983 and 1984 and annual increases thereafter until the sequence ends in 1987.

Interestingly, a very strong (+10 standard deviation) sea ice anomaly is present in this time series for May and June, 1987, the result of a late occurrence of the "Odden". Given the unusualness of this anomaly with respect to the rest of the data sequence, it probably does not reflect any climate state changes.

2.8 East Siberian Sea

In the preceding examples, seven regions of distinct linear trends in Arctic sea ice have been described. For comparison, an area of no apparent trend in sea ice concentration can be seen in Figure 3 in the East Siberian Sea; its time series are plotted in Figure 5. It is interesting to note the similarities of the mean concentration and concentration standard deviation time series, yet the striking differences between the anomaly plots of the East Siberian Sea and the Arctic Ocean locations. It is clear that although the ice anomalies in the East Siberian Sea are small in absolute magnitude, they can be large, relative to the highly stable ice concentrations in the Arctic Ocean.

3 DISCUSSION

The results of the image trend analyses show several regions of statistically significant trends in Arctic sea ice concentrations between 1978 and 1987, most notably decreasing iciness in the Barents and Okhotsk Seas. These trends have not been previously identified in other studies (e.g., Parkinson and Cavalieri, 1989; Chapman and Walsh, 1993). Although such previous analyses did examine data from these areas, they did so as part of broader geographic regions, within which smaller locations of significance would not be visible. One of the strengths of the per-pixel processing inherent to hypertime image analysis is that the data are analyzed at the spatial resolution of the imagery. Further, since arbitrary regional boundaries are not imposed on the data, natural spatial groupings emerge which could provide important clues for defining sea ice processes and the linkages between the cryosphere and its adjacent planetary systems.

Although the strengths of the sea ice concentration trends observed in some locations in the Arctic are quite strong, there are several factors which may account for some of these changes. All of the regions exhibiting significant, non-chance trends in ice concentration over the SMMR period occur in the seasonal ice zone. These are areas which typically become ice-covered in winter and ice-free in summer. The seasonal ice zone is a region in which the ice cover is more susceptible to the shorter term effects of passing weather systems, which can impart a particularly high variability on the ice conditions at daily to annual time scales. The extent to which the inter-annual variability in the plotted time series of Figure 5 are due to weather "noise" or climatic "signal" is impossible to tell over such a short period. The Sea of Okhotsk and the Barents Sea are the only regions where significant decreases in ice concentrations can be said to have occurred between 1978-87.

There is a well documented "see-saw" effect of uncertain origin in ice conditions between portions of the eastern and western Arctic basin (Lemke *et al.*, 1980). Thus, more ice in one sector is generally accompanied by less ice in the opposite zone. This effect is particularly

evident in a comparison of mean sea ice concentration plots between the Barents Sea and the Labrador Sea (Figure 5), but may be at work in different parts of the Arctic as well. It is possible that the patterns of increasing and decreasing ice concentrations mapped in Figure 3 are a simple reflection of where in the see-saw oscillation the SMMR data series begins and ends. That is, the nine year span of the data in question could have started during a period of heavy ice in the Eurasian Arctic and as part of the see-saw cycle ended during a time of light ice. If the beginning and end dates of the series were different or the data series was longer, the mapped trends may appear quite differently. The interannual variability in sea ice extents is such that the time period selected for analysis can make a large difference in the magnitude and direction of the resulting trends.

It has been shown that El Niño - Southern Oscillation (ENSO) events in the tropical South Pacific Ocean have strong teleconnections with various regions of the Arctic with the strongest signals between heating anomalies in the tropics and polar regions occurring in winter (Walsh, 1983; Niebauer and Day, 1989; LeDrew, 1992a). A particularly strong ENSO event occurred in 1982-83, in the middle of the SMMR data record. A review of the plots in Figure 5 show, without exception, that at some time in the two year period immediately following this event either anomalously low or high ice concentrations can be found in each region sampled. These findings lend further evidence to the theory that ENSO events are indeed measurable in the Arctic environment and they further suggest that changes in sea ice chronologically follow the tropical anomalies so they cannot be used as predictor variables for future ENSO events.

In this report the statistical technique of linear regression has been used to identify regions of potentially significant trends in ice concentrations. It should be noted, however, that one of the basic assumptions of linear regression was violated in this approach: that the data are not autocorrelated. Clearly, these data include a significant amount of autocorrelation in the seasonal signal. This approach can still be considered valid, however, since the slope of the linear regression line is only employed as a potential indicator of significant trends, and not as a predictor measure. Trend images are used herein as keys to identifying those regions where significant sea ice processes may be occurring. It would not be correct to use the derived trend as a measure of absolute change in ice concentrations over the SMMR period or as a predictor of future changes.

It should be kept in mind that the anomalies have been calculated with respect to themselves and not an independent data set, such as longer-term ice concentration normals. Therefore, a certain number of "significant" anomalies are to be expected as part of the assumption of a Gaussian distribution for these data. It is impossible to tell whether any "significant" anomalies found herein are significant in terms of climatic normals.

In this report, an image trend analysis technique was developed to find trends in long temporal image sequences. Although the technique can be quite effective in highlighting the spatial distribution of temporal trends, it is easily influenced by anomalous values, especially near the ends of the data series, so the results should be interpreted with caution. When used in conjunction with interpretative time series plots sampled from the image stack, however, image trend analysis can provide valuable insights into the temporal processes at work within the data.

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